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Environmental Analysis of Fleet-Wide Implementation of Delayed Deceleration Approaches

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The capabilities and benefits of fleet-wide implementation of the delayed deceleration approach are presented through the modeled analysis of a day of implementation at Boston Logan International Airport. Conventional approach procedures can often involve early configuration in the flight trajectory, which results in aircraft having to deploy high-lift configurations early and thus having to operate at higher thrust levels. Employing a delayed deceleration approach involves delaying the configuration of high-lift devices and maintaining higher speeds for longer, thus allowing lower thrust settings and reducing approach fuel burn and community noise. There are challenges, however, with implementing delayed deceleration approach procedures on a fleet-wide basis. The deceleration rate for a given approach procedure can vary significantly depending on aircraft type, weight, and the procedure flown. In this work the study of an average day at Boston Logan International Airport is presented to analyze the feasibility and benefits of implementing delayed deceleration approaches on the most common aircraft and assesses the capability of sequencing multiple delayed deceleration approaches into a given runway. The results for the representative day indicate that 97% of sequences involving aircraft that account for 83% of the commercial fleet for Boston Logan International Airport in 2017 do not introduce a breach of separation when implementing a delayed deceleration approach. Furthermore, implementing the delayed deceleration approach provides an average fuel burn savings of 21.4% and reduces the ground track distance exposed to configuration noise by and average of 9 nmi. Such results provide evidence that the delayed deceleration approach and decision support tools should be implemented for commercial aircraft.

I. Nomenclature

ANOPP	=	NASA Aircraft Noise Prediction Program
ASD-B	=	Automatic Dependent Surveillance-Broadcast
ASDE-X	=	Airport Surface Detection Equipment, Model X
ATS	=	Air Traffic Service
BADA	=	Eurocontrol's Base of Aircraft DAta
BOS	=	Boston Logan International Airport
dB	=	Decibels
DDA	=	Delayed Deceleration Approach
ΔA	=	Area of community noise savings
Δf	=	Ground track distance between first configurations deployment
ft	=	Feet
ILS	=	Instrument landing system
kias	=	Indicated airspeed in knots
MLAT	=	Multilateration
nmi	=	Nautical miles
SEL	=	Sound exposure level
TASOPT	=	Transport Aircraft System OPTimization
PBN	=	Precision-based-navigation
RNAV	=	Area Navigation
RNP	=	Required navigation performance

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II. Introduction

Conventional approach procedures can often involve early deceleration in the aircraft approach trajectory, which implies an early deployment of high-lift devices and the aircraft operating at above idle thrust levels for long distances before stabilization [1]. Such procedures result in high approach fuel burn and emissions, in addition to high noise levels for communities surrounding airports [1–4]. Due to advancements in precision-based-navigation (PBN) techniques, such as area navigation (RNAV) and required navigation precision (RNP), flight track densities have increased over particular communities surrounding airports [3]. Frequent flyovers coupled with noisy conventional approach procedures have been observed to correlate with an increase in noise complaints from communities surrounding airports [3]. The Delayed Deceleration Approach (DDA) procedure is an advanced noise abatement approach procedure that has shown potential to mitigate such consequences [1, 5]. A DDA procedure involves delaying the start of deceleration while upholding the safety requirement that the aircraft must be fully configured and at the final approach speed before the stabilization point [1]. This enables employing high-lift devices later in the approach sequence; thus remaining in a clean configuration for longer and delaying the onset of flap and slat noise, reducing thrust, and lowering engine noise [1].

Previous work has shown that a DDA procedure is not only feasible when assessing a single aircraft, but noise effective and fuel efficient [1–3, 5, 6]. A DDA procedure had been successfully demonstrated on a B777-200 during the 2019 ecoDemonstrator program, and it had been found that DDA procedures can provide 4-8 dB in noise reductions for regions under the flight track far from stabilization compared to standard procedures [1]. Previous work, however, does not address the restrictions that a fleet setting provides. On an approach into a given runway, the surrounding aircraft introduce spatial constraints that can potentially hinder the ability to implement DDA to its full potential as DDA has a significant impact on along-track distance to touchdown. A safety requirement for approach procedures is that an aircraft must maintain significant separation between it and the surrounding aircraft [7]. In order to justify the benefits of DDA procedures and promote the use of decision support tools such as the German Aerospace Center Low Noise Augmentation System [8], it is necessary to study them on a fleet-wide basis. DDA procedures depend on deceleration rates which vary according to aircraft type, weight, and the procedure flown. A fleet of aircraft can follow the same altitude profile on an approach with vastly different deceleration rates. For example, Fig. 1 presents Airport Surface Detection Equipment, Model X (ASDE-X) data at Boston Logan International Airport (BOS) recorded in 2017 of approach procedures for multiple aircraft into runway 22L that perform a 4000ft level-off. Indicated in black is a velocity profile that has a delayed deceleration whereas in blue is a more conventional, early deceleration. In this work, we will restructure such conventional procedures to follow a delayed deceleration velocity profile and assess the changes in environmental impacts.

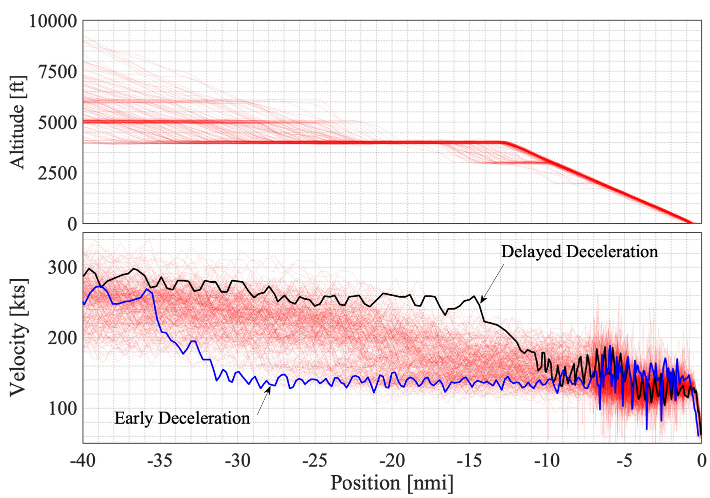


Fig. 1 ASDE-X data of approach procedures into runway 22L at Boston Logan International Airport.

The ability for different aircraft to perform the same altitude profile with different deceleration rates is both advantageous and hindering to fleet-wide DDA implementation. The ability to alter the deceleration rates while flying the same altitude profile invites the possibility of implementing DDA for an individual aircraft. However, when implementing DDA procedures in a fleet setting, the surrounding aircraft introduce spatial constraints that must be considered when evaluating the overall potential and benefits. DDA procedures are inevitably faster than conventional approach procedures as the aircraft maintains a higher velocity for a longer duration of the approach procedure. Therefore, it is crucial to thoroughly study the impact DDA procedures have on the approach timing among an array of aircraft within a given fleet. In doing so, identifying aircraft and sequencing limitations will establish necessary guidelines for safe implementation of DDA procedures on a fleet-wide basis. This paper will assess DDA implementation through the study of an average day of approach sequences performed by the most common aircraft landing at Boston Logan International Airport for the year of 2017. The remainder of this paper is structured as follows: a breakdown of the modeling framework is described in section III, including the aircraft performance, flight profile generation, aircraft noise, fuel burn, and sequential timing in sections III.A, III.B, III.C, III.D, and III.E, respectively, section IV describes the case study and analysis performed, including an example that demonstrates the analysis procedure and the results of the study, and finally in section V is a detailed discussion of the findings.

III. Modeling Framework

To assess the capabilities and benefits for fleet-wide implementation of DDA procedures, a framework that consists of models for aircraft performance, flight profile, fuel burn, sequential timing, and aircraft noise is needed. This framework produces a baseline flight profile reflecting a conventional approach procedure from provided ASDE-X data for a given aircraft and constructs a delayed deceleration approach procedure that mimics the altitude versus distance of the baseline profile but alters the speed and configuration. These flight profiles are then used to perform aircraft noise, fuel burn, and sequencing analysis as described in detail in sections III.C, III.D, and III.E, respectively. The implemented framework is presented in Fig. 2.

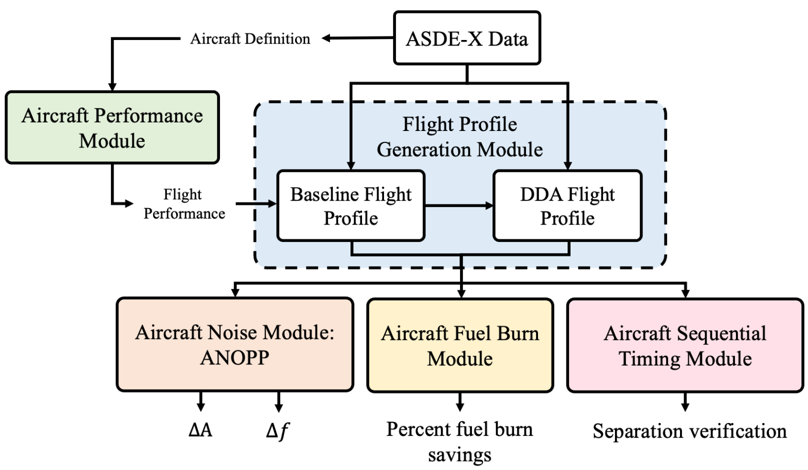


Fig. 2 Delayed deceleration approach benefit assessment and modeling framework.

A. Aircraft Performance Module

Approach procedures may include frequent changes in thrust, aircraft configuration, altitude, and velocity which have varying impacts on the noise and fuel burn depending on the given state. Thus to precisely model the noise of an aircraft, detailed component-level aircraft and engine parameters are needed. In this framework, Transport Aircraft System OPTimization (TASOPT) is used to supply engine parameters necessary for computing thrust settings and component noise. TASOPT utilizes physics-based computations to predict the weight, performance, and aerodynamic characteristics of a "tube and wing" transport vehicle [9]. This work focuses on aircraft that are currently in use, thus airframe geometry is determined based on publicly available aircraft performance and geometry data [10]. Eurocontrol's Base of Aircraft DAta (BADA) [11], a database of aircraft performance parameters from aircraft manufacturers, provides detailed drag data as a function of configuration setting and speed which is necessary for modeling the flight profiles within the flight profile generation module.

B. Flight Profile Generation Module

In this study, ASDE-X data from Boston Logan International Airport (BOS) in 2017 is used to model flight procedures for given aircraft. Altitude and ground speed as a function of distance to touchdown are extracted from ASDE-X data to generate the corresponding thrust levels and calculate the deceleration rate of the flight profile using a point mass model based on the drag characteristics, weight, and configuration speed limitations according to the aircraft [3].

The flight procedure is modeled on a segment-by-segment basis. To identify the deployment location of high-lift devices, the ground speed provided by ASDE-X data is converted to indicated airspeed in knots (kias) where the effects of weather are neglected, and the weight of the aircraft is assumed to be 75% of the maximum take-off weight. The allowable speed region for a given high-lift configuration is identified as the range between the maximum allowable speed of the configuration setting, provided by BADA in kias, and the minimum safe speed, calculated using the maximum lift coefficient of the configuration setting also provided by BADA. A given configuration velocity is then assumed to occur at the midpoint of the allowable speed region. The deployment of landing gear is assumed to occur at 2000 ft or before the stabilization point, which is identified according to when the velocity of the ASDE-X data stabilizes to a final approach speed [5]. By constraining the flight path angle and velocity, in addition to the flight performance characteristics provided by BADA, a force-balance is used to model the thrust levels for each segment. The resulting flight profile including the altitude, velocity, and thrust as a function of distance to touchdown is the complete baseline flight procedure model.

In a DDA procedure, the aircraft is assumed to maintain the highest allowable airspeed below 10,000 ft of 250 kias in a clean configuration. The aircraft will then perform an idle-thrust deceleration that is modeled on a segment-by-segment basis assuming the same altitude versus distance to touchdown as the baseline profile. The velocity profile is reconstructed through solving the point-mass model for the distance required to achieve the velocity for each configuration setting, where the velocity of each configuration is assumed the same as the baseline profile. In doing so, this determines the closest point to touchdown that deceleration must begin to ensure the safety requirement of being fully configured and at the final approach speed before the stabilization point. This identifies new high-lift configuration locations and provides a DDA procedure that maintains the same altitude profile as the modeled flight procedure [1].

C. Aircraft Noise Module

To model the noise of aircraft performing conventional and delayed deceleration approaches, where the impacts due to the deployment of high-lift devices, varied thrust levels, and varied speeds must be considered, a component-based noise analysis methodology incorporating the NASA Aircraft Noise Prediction Program (ANOPP) [12] is utilized. ANOPP predicts noise levels according to physics-based and semi-empirical functional relationships between aircraft noise sources and operation states. Airframe and engine performance parameters in addition to observer positions, flight velocity, position, and configuration settings are required for ANOPP's various models.

The modules within ANOPP used to model engine noise include the Stone jet noise method [13], the Heidmann fan noise method [14], and the Society of Automotive Engineers (SAE) core engine control method [15]. For airframe noise, the Fink methods [16] were used for wing and tail trailing edge noise and methods produced by Guo were used for slats, flaps, and landing gear noise [17–20]. The primary noise metric at observer locations used in this paper is the sound exposure level (SEL). In order to determine the noise impacts of implementing a DDA procedure, detailed inputs of the aircraft geometry and internal engine states including performance at off-design conditions as well as high-lift device and landing gear configuration changes throughout the flight procedure for both the baseline and DDA flight profile is provided by the Flight Profile Generation Module. For this work, a work-balance based component matching turbofan engine model incorporated into TASOPT [9] is used to obtain the relevant engine parameters as a function of the thrust and velocities for each flight determined from the Flight Profile Generation Module. Additionally, the flight procedure must be assessed with accurate aircraft performance characteristics which are provided by the aircraft performance module.

Previous work indicates that the first high-lift deployment is crucial to the overall community noise impact [1]. The along-track distance from the first deployment during the baseline procedure to that of the DDA procedure (Δf) indicates a region that is subjected to configuration noise during the conventional procedure that is not in the DDA procedure. Although the area of community noise savings (ΔA) is also dependant on the altitude and atmospheric attenuation, Δf expresses the amount of noise savings of implementing DDA for a given flight, and is the metric used in this paper to convey the noise savings provided by a DDA procedure when among a fleet setting.

D. Aircraft Fuel Burn Module

Fuel burn rate is provided for a given aircraft in the aircraft performance module as an output of BADA. Within the flight profile generation module, the fuel burn rate is modeled on a segment-by-segment basis and the time elapsed per segment is determined according to the velocity of each segment. Therefore, the fuel burn is the summation of the product of fuel burn rate and time elapsed for each segment defining the flight profile, for both the baseline and DDA procedure. To provide commonality when comparing the fuel burn during each approach procedure, the total approach fuel burn is defined in this work as the total fuel burn from 30 nmi to touchdown. The output of the aircraft fuel burn module is the percent of fuel burn savings provided by DDA, that is the percent difference in approach fuel burn between the baseline procedure and DDA procedure of a given flight.

E. Aircraft Sequential Timing Module

When implementing DDA procedures within a fleet, a given aircraft is subjected to the spatial constraints of the surrounding aircraft. In order to not breach separation during the approach sequence, aircraft must maintain a minimum of 5 nmi of horizontal separation or 1000 ft of vertical separation, based on radar, ASD-B, and/or MLAT systems [7]. This minimum can be lowered to 3 nmi by ATS authority if system capabilities permit, and when within 10 nmi of the runway threshold, the minimum can be as low as 2.5 nmi when criteria listed in ICAO Doc 4444 section 8.7.3.2 are met [7]. The timing of a delayed deceleration approach can vary significantly from a traditional approach depending on the deceleration capabilities of the aircraft. This framework determines the position of the aircraft as a function of the time provided by the flight profile generation module for both the baseline and DDA procedure to determine if the faster DDA procedure introduces a separation breach into the sequence. The horizontal and vertical separation of the approach sequence is evaluated from 40 nmi to touchdown, where the start time of each flight is taken to be the time at which the aircraft was 40 nmi to touchdown in the ASDE-X data.

IV. Fleet-Wide DDA Environmental Analysis

A case study was conducted to demonstrate environmental impacts of community noise and fuel burn of fleet-wide implementation of DDA. As an example fleet for this study, an average day according to ASDE-X data from Boston-Logan International Airport from 2017 was used. There was an average of 518 arrivals per day for the year of 2017, and the closest representative day was February 2, 2017 with 512 arrivals, of which 330 identified as commercial flights. The frequency of commercial landings for February 2 was assessed to determine the most common aircraft, see Fig. 3. The Airbus 320 (A320) and 321 (A321), Boeing 737 (B737), 737-800 (B738), and 737-900 (B739), and Embraer 190 (E190) account for 83% of the day's fleet, when omitting small aircraft such as turboprops and business jets as they are not considered in this analysis. The distribution of aircraft for the case study is within 1% accuracy of the distribution for the entirety of the data, indicating that this case study is a valid demonstration of the behaviors on a larger scale.

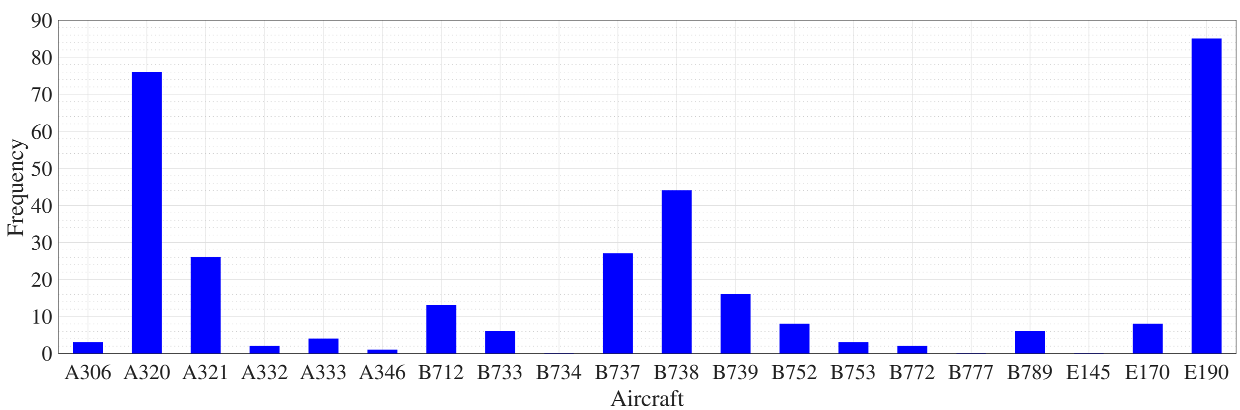


Fig. 3 Aircraft frequency of ASDE-X data for February 2, 2017.

Analysis of multiple aircraft performing approach sequences is performed with the motivation of understanding the current challenges of unanimously implementing DDA. Particularly, the aim of this study is to assess how sequences of aircraft with different flight performance, deceleration rates, and following arbitrary altitude profiles perform when employing DDA. By modeling sequences of true conventional approach procedures and the corresponding DDA, this work attempts to identify whether a seamless transition to DDA procedures is possible, or if aircraft deceleration differences hinder a fleet-wide implementation.

It is assumed that aircraft of same aircraft family have similiar drag characteristics, thus having minimal discrepancies in their deceleration rates. Therefore, instances of the A321 is modeled using the A320 drag and noise models for simplicity. Likewise, the B737 and B739 are modeled using the B738. Sequences of the 3 aircraft (A320, B738, and E190) were studied for the 27 possible sequences. A total of 77 sequences of the listed aircraft occurred on February 2 and the distribution of sequence types are presented in Fig. 4. The sequence type is defined by the aircraft and order of occurrence, for example the sequence ABE consists of an A320 followed by a B738 and then an E190. The most common sequences include combinations of the A320 and B738: ABA, BAB, and ABB. In order to illustrate the details of the analysis performed a demonstrative example of an ABE sequence flown into runway 22L at BOS on February 2, 2017 is provided in the following section.

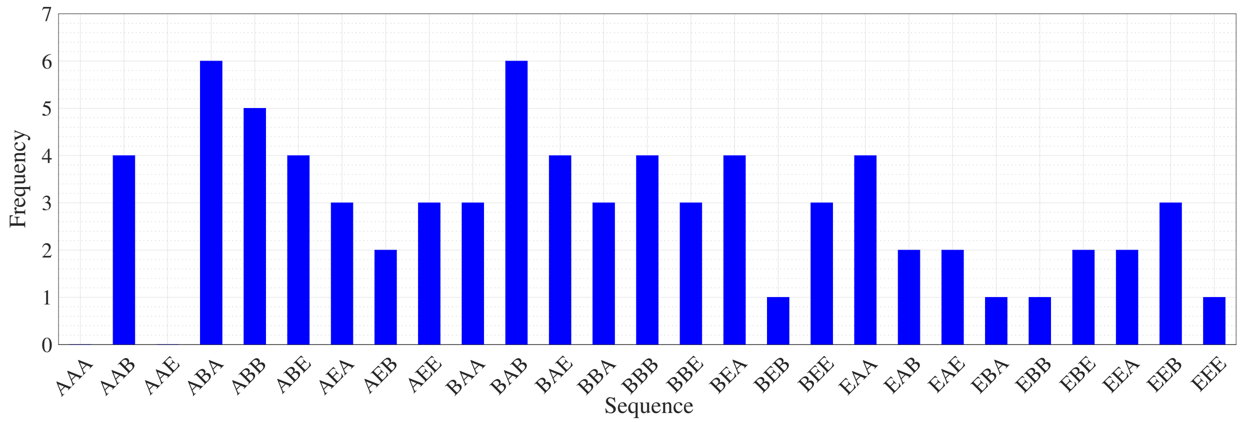


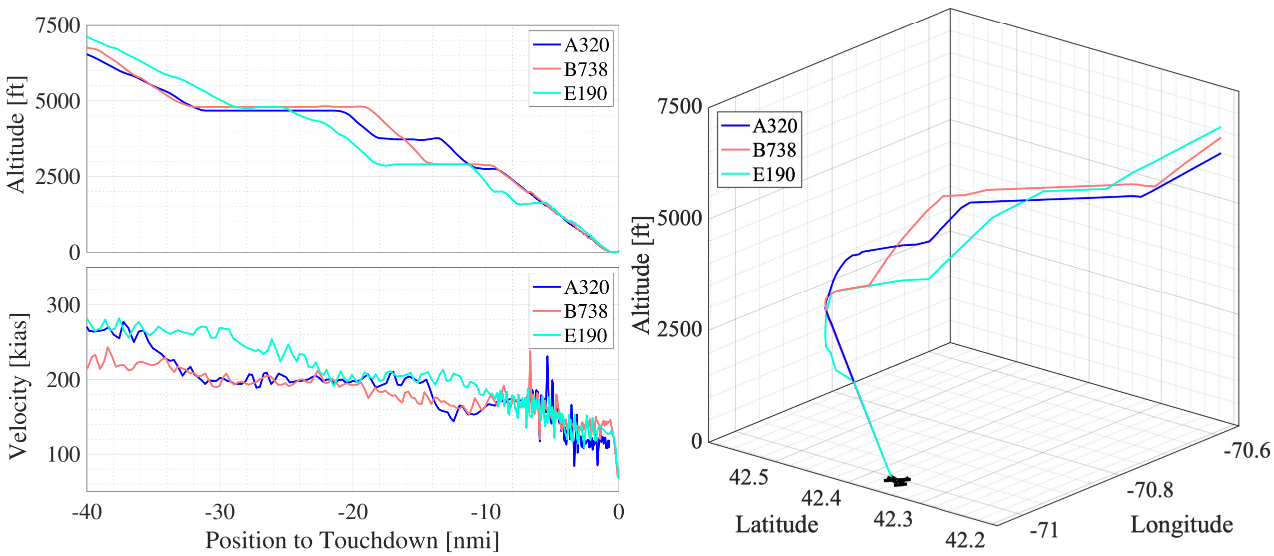
Fig. 4 Aircraft frequency of ASDE-X data for February 2, 2017.

A. Demonstration of DDA Implementation on a A320, B738, E190 Sequence

An example sequence of the A320, B738, and E190 is used to demonstrate the analysis completed for a given sequence. The ASDE-X data of the altitude and velocity profiles for the aircraft in the sequence being studied is presented in Fig. 5a, and the altitude as a function of latitude and longitude is plotted in 3 dimensional space in Fig. 5b. The sequence consists of an A320 performing 3 level-off segments of 10.5 nmi, 4.5 nmi, and 1.5 nmi at 4675 ft, 3750 ft, and 2750 ft, respectively. Following the A320, the B738 performs a 13 nmi level-off 4800 ft and a 4.5 nmi level-off at 2900 ft. The A320 and B738 begin their final descent around 9 nmi from touchdown. Finally, the E190 performs a 4 nmi level-off at 4800 ft, a 6.5 nmi level-off at 2900 ft, and then two short level-offs before intercepting the Instrument Landing System (ILS) glide slope at 5.5 nmi from touchdown. Complex altitude profiles like the ones presented in this example highlight the challenges of constructing a DDA procedure. The dynamics of the system changes according to the flight path angle for a given segment, affecting the deceleration rate and adding complexity to identifying the proper location for each configuration deployment.

The velocity profiles indicate that the A320 and B738 begin decelerating early in the landing sequence, the B738 had already decelerated to a velocity of 220 kias prior reaching 40 nmi to touchdown. The E190's velocity hovers near 250 kias until 29 nmi to touchdown before decelerating to 200 kias and maintains this velocity for nearly 10 nmi. Such velocity profiles depict conventional flight procedures that do not employ DDA. By filtering the velocity data using a moving average with a window of 5, a clear representation of the velocity is used to determine configuration deployment locations and the stabilization point as described in section III.B. The data presented in Fig. 5 is used as inputs into the aircraft performance module and flight profile generation module of the framework outlined in Fig. 2 as the altitude and velocity profiles used to construct a model of the flight profile for both the baseline and DDA procedures of each aircraft according to the framework described in section III.B.

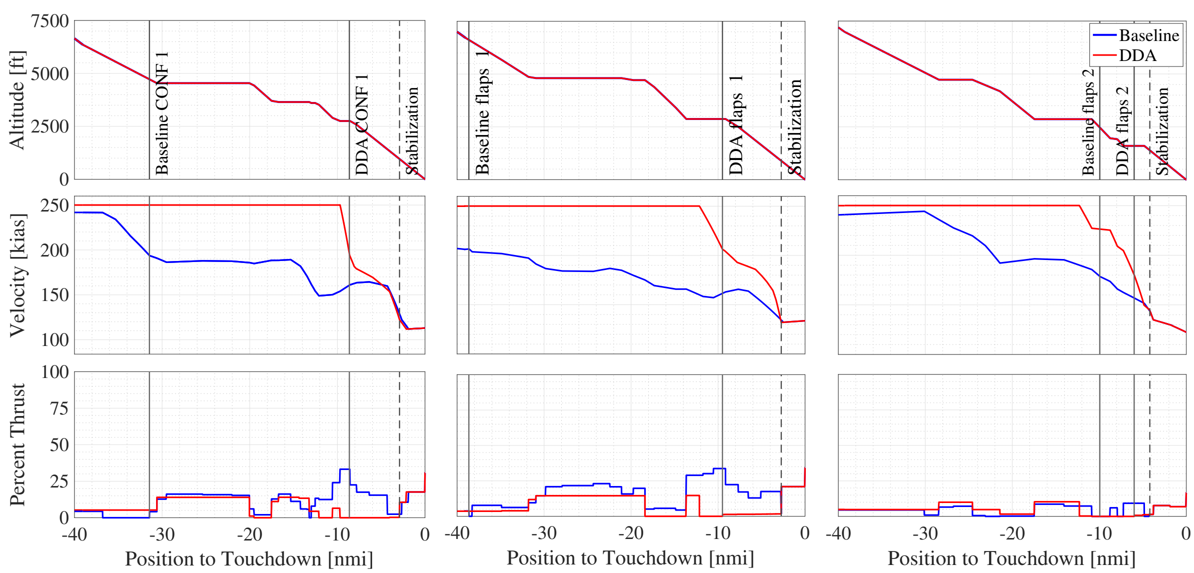
A comparison of the baseline and DDA flight profile models for the A320, B738, and E190 are presented in Fig. 6a, Fig. 6b, and Fig. 6c, respectively. The first configuration for each procedure is indicated in the figures to highlight the ground track distance exposed to configuration noise during the baseline procedure that is eliminated by DDA procedure (Δf). The primary difference between the baseline and DDA profiles for a given flight procedure is the modification of



(a) Altitude and velocity profiles.
(b) Latitude, longitude, and altitude.

Fig. 5 ASDE-X data of demonstration sequence: A320, B738, E190.

the deceleration rate and the consequential variation in thrust. In order to accurately model a DDA approach it is crucial to identify when the aircraft must begin deceleration, as described in section III.B. Notable characteristics of the baseline profiles in the case studied are as follows. The A320 and B738 deploy the first configuration at 31.5 nmi and 38.6 nmi to touchdown, respectively, which is substantially early configurations that results in excess fuel burn and community noise. Alternatively, the E190 initiated the first configuration deployment at 10 nmi to touchdown. Additionally, the baseline velocity profiles for the A320 and B738 indicate the aircraft accelerated after it began deploying high-lift devices, which result in an increased percent thrust that is evident in both of the flight profiles.

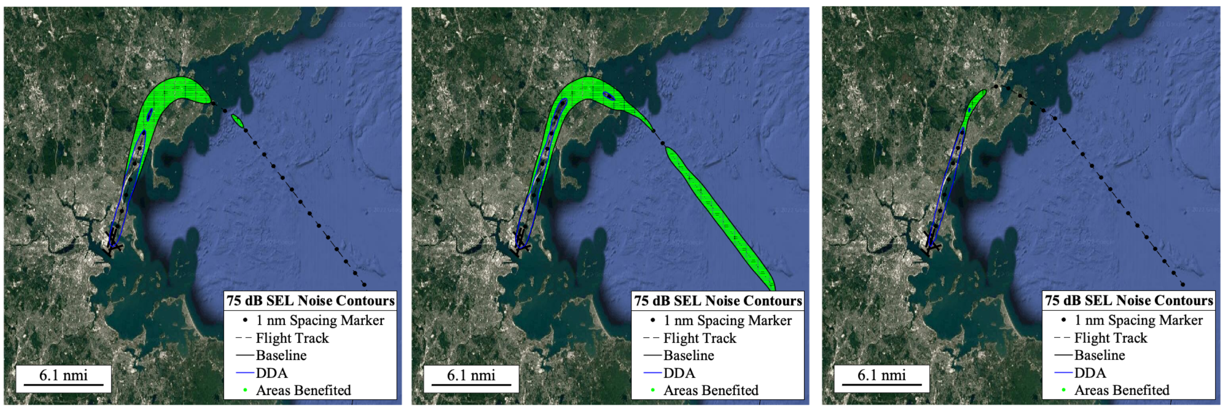


(a) A320
(b) B738
(c) E190

Fig. 6 Flight profile comparison of baseline and DDA model with initial configuration deployment indication.

The ground track distance between the first configurations of the baseline and DDA procedures (Δf) for the A320, B738, and E190 are 22.8, 29.5, and 4.1 nmi, respectively. The complete profiles were input into the aircraft noise, fuel burn, and sequential timing modules of the framework in Fig. 2 to assess the benefits and capabilities of this sequence of aircraft.

The 75 dB sound exposure level (SEL) noise contours of the A320, B738, and E190 comparisons are provided in Fig. 7a, Fig. 7b, and Fig. 7c, respectively. Indicated in black is the 75 dB SEL noise contour for the baseline procedures, and likewise, in blue is the DDA contour. Highlighted in green is the area of community noise savings (ΔA), of which is not subjected to noise when a DDA procedure is employed. The community noise savings recorded for the A320, B738, and E190 are 10.1, 20.1, and 1.4 nmi^2. The one-dimensional ground track distance, Δf, corresponds to ΔA as described in section III.C. The location along the flight trajectory where the noise contour starts, in this example, corresponds to the location of first configuration deployment due to the onset of configuration noise. Although this may not be the case in all instances, Δf is the metric used to represent the community noise reduction resulting from DDA implementation for this paper as it simplifies the computation time requirements when studying fleet-wide implementation.



(a) A320 (b) B738 (c) E190

Fig. 7 75 dB sound exposure level noise contour comparison of DDA and baseline profiles.

In order to measure approach fuel burn savings, this paper marks the approach procedure to begin at 30 nmi to touchdown. The percent of fuel burn savings for a DDA procedure in comparison to the baseline flight is calculated according to the procedure described in section III.D for the A320, B738, and E190 to be 37.5%, 50.6%, and 18.8%, respectively. The area of the baseline noise contour, DDA noise contour, and the area of community noise savings (ΔA), along with Δf and the percent savings in fuel burn provided by the DDA procedure relative to the baseline for each aircraft is summarized in table 1. According to the data for this sequence the B738 benefits the most from a DDA procedure.

Table 1 Environmental benefits for employing DDA on example sequence.

Aircraft	Fuel Burn Savings	Δf	Noise Contour Area [nmi^2]		
	[%]	[nmi]	Baseline	DDA	ΔA
A320	37.5	22.8	15.9	5.8	10.1
B738	50.6	29.5	26.1	6	20.1
E190	18.8	4.1	5.5	4.1	1.4

The final component of the analysis is to assess how the DDA procedures perform in a fleet setting. This is done by assuming both the baseline and DDA procedure start from 40 nmi to touchdown at the same time. Additionally, a concrete separation criteria that is consistent with the referenced ASDE-X data is required. Through analysis of aircraft separation among the ASDE-X data for February 2, 2017, the horizontal separation minimum is assumed to have been lowered by ATS authority to 3 nmi and 2.5 nmi within 10 nmi of the runway threshold, as described in section III.E. Thus, a breach of separation is considered to occur if the horizontal and vertical distance between two consecutive aircraft is below 3 nmi and 1000 ft, respectively, and reduces to 2.5 nmi of horizontal separation and 1000 ft of vertical separation within 10 nmi of the runway threshold. Four successive snapshots of the A320, B738, and E190 approach sequence is presented in Fig. 8. The time elapsed, indicated in the figure, refers to the time since the first aircraft (A320) started its approach procedure at 40 nmi to touchdown. Each plot includes the three altitude profiles with markers that signify the baseline and DDA locations of a corresponding aircraft.

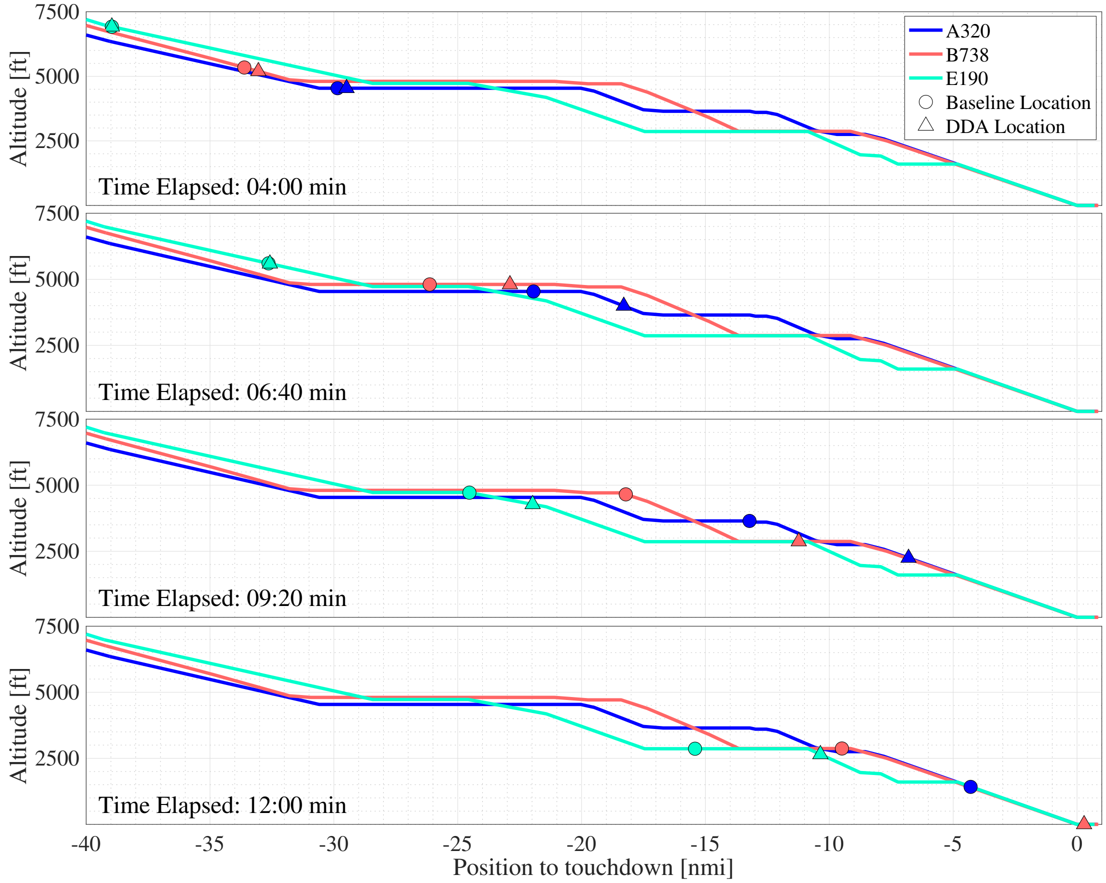


Fig. 8 Aircraft positioning display of demonstration sequence: A320, B738, E190.

In this sequence, the second aircraft reaches 40 nmi to touchdown 1 minute and 30 seconds after the first, and the third aircraft reaches 40 nmi to touchdown 2 minutes and 20 seconds after the second. The first two aircraft start with a horizontal and vertical separation of 2.9 nmi and 1000 ft, respectively, thus satisfying the separation requirements. The E190 follows the B738 with larger separation of 5.2 nmi horizontally and 1512 ft vertically, which corresponds to the larger timing delay previously mentioned. At a time elapsed of 4 minutes, the A320 and B738 are starting to decelerate in their baseline procedures, while the E190 has just passed 40 nmi to touchdown and there is no obvious change in aircraft positioning. The separation of the first two aircraft is no longer satisfied by the vertical separation, but rather the horizontal separation of 3.8 nmi for the baseline and 3.6 nmi for the DDA. As the aircraft progress, the horizontal separation between the first two aircraft's DDA procedures reaches its maximum of 4.7 nmi at time elapsed of 6 minutes and 14 seconds, and maintains this for the remainder of the procedure. The baseline procedure does not reach the same separation distance until 7 minutes and 52 seconds. The separation between the second and third aircraft significantly increases by the DDA procedures as it reaches 10.7 nmi of horizontal separation at a time elapsed of 8 minutes and 13 seconds and maintains such distance for the remainder of the sequence. Alternatively, the horizontal separation in the baseline procedure peaks at 6.5 nmi after 7 minutes and 12 seconds, and steadily declines until the B738 touches down at a time elapsed of 14 minutes and 39 seconds. This is expected given that in the conventional procedure the E190 performs a later deceleration than the proceeding B738, as evident Fig. 6. Thus the DDA procedure accelerates the B738 approach more significantly than the E190, which is evident by the lack of deviation in the E190 positioning in the E190 positioning for the first two snapshots. For this sequence, it is clear that no aircraft breach separation when DDA procedures are performed, rather the DDA procedures introduce a larger horizontal separation for longer durations of the approach sequence.

B. Fleet-Wide Environmental Impacts and Separation Analysis Results for DDA Implementation

The procedure demonstrated in section IV.A was completed for the 77 sequences outlined in Fig. 4 of the A320, B738, and E190 that occurred on February 2, 2017 according to the ASDE-X data. The sequences studied included a wide array of approach sequences arriving into runways 22L, 27, and 33L at BOS and are depicted in Fig. 9. Each

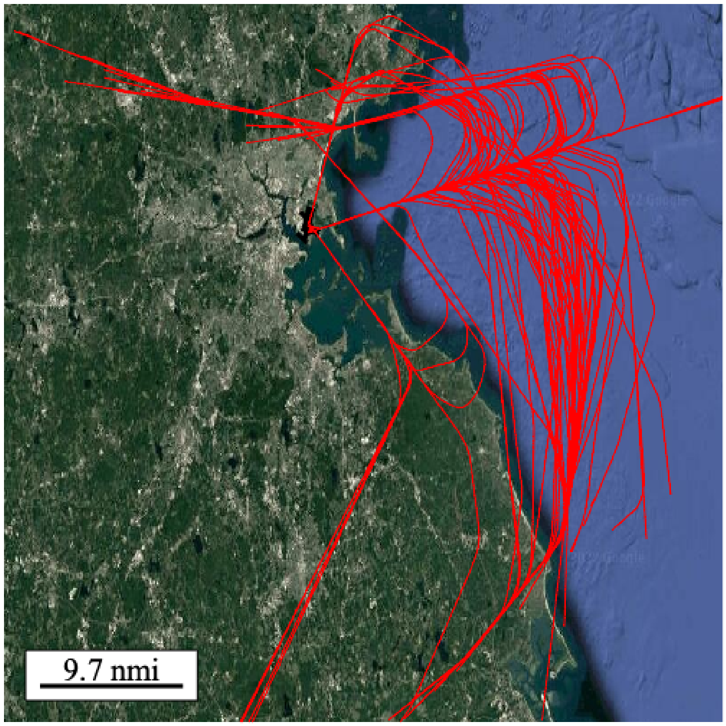


Fig. 9 Flight tracks of the fleet from February 2, 2017 used for the case study.

flight track represents a sequence of three consecutive aircraft that were modeled for the conventional procedure of the ASDE-X data and a modified DDA, the environmental impacts of implementing DDA were recorded, and the timing of the sequence was analyzed. A summary of the average fuel burn savings provided by the DDA procedures and ground track distance between the first configurations of the baseline and DDA procedures (Δf), is presented in table 2.

Table 2 Fleet-wide percent fuel burn and noise savings provided by DDA implementation

Aircraft	Average Fuel Burn Savings [%]	Average Δf [nmi]
A320	20.4	9.0
B738	29.2	10.2
E190	11.4	6.9
Average	21.4	9.0

Consistent with the results of the example presented in section IV.A, the aircraft with the biggest potential for savings is the B738, with an average fuel burn savings of 29.2% and an average Δf of 10.2 nmi. The B738 has more configurations than both the A320 and E190, with the E190 having the least. This suggests that the B738 has the ability to perform more diverse deceleration rates than the other aircraft. Also, fewer configuration settings, like that of the E190, cause the aircraft to maintain higher speeds and are seen to more commonly follow procedures similar to DDA, thus resulting in smaller averages for fuel burn and noise savings. However, such procedures generally involved more specific altitude profiles with low level-offs late in the approach procedure where the aircraft decelerates. However, as this study indicates, DDA procedures can be implemented regardless of the altitude profile performed. Additionally, procedures involving late deceleration were occasionally evident among the ASDE-X data for all the aircraft studied, which ultimately lowered the averages summarized in table 2. This indicates that there are pilots and airlines making an effort to perform more environmentally conscious approach procedures, however, as this work has shown, DDA procedures are capable of being more widely implemented and can provide impactful benefits in regards to fuel burn and community noise.

As summarized in table 3, 85.7% demonstrated a clean implementation of DDA indicating that the timing delays identified from the ASDE-X data is sufficient to safely perform DDA. An additional 11.7% encountered a breach of separation in the baseline profile that was no longer present in the DDA profile. As illustrated in Fig. 8, the delayed deceleration commonly introduces additional horizontal separation that is not present in the baseline procedures. Also, in such cases a subtle breach of the separation criteria was identified at the beginning of the approach sequences that were corrected by the DDA procedures. In the remaining 2.6% of sequences, a breach of separation was identified in the baseline case that was not solved by DDA, implying that holding delays may be necessary.

Table 3 Fleet-wide separation results for optimal DDA implementation

Separation Result	Number of Cases	Percentage [%]
Clean Separation	66	85.7
Improved Separation	9	11.7
Separation Concerns	2	2.6

In 97.4% of the cases studied the horizontal separation increased in comparison to the baseline sequences, indicating that by delaying the deceleration of all flight procedures, the horizontal spacing between succeeding aircraft increases. This implies that the studied aircraft, of which encompass 83% of commercial flights, do not present separation concerns when sequenced together. Further analysis needs to be performed for sequences including the remaining aircraft that were not considered.

V. Discussion

The presented study assesses the capabilities and benefits of implementing delayed deceleration approaches for the most common commercial aircraft at BOS on an average day in 2017. The resulting fuel burn savings and community noise reductions identified remain consistent with that of previous work, of which evaluated DDA on an individual aircraft basis. Two cases showed a breach of separation that was not corrected by the DDA procedure, both of which occurred when an E190 was followed by a B738. Such sequences performed DDA without concerns of breaching in 8 other cases, implying that the aircraft are capable of sequencing DDA procedures without breaching separation and that other factors may be influential to DDA performance. Further analysis needs to be performed to assess the dependency that a DDA procedure has on the altitude profile flown and the impact it has on deceleration rates and timing. Additionally, the cases with separation concerns met separation criteria not in the horizontal direction, but in the vertical direction. Nonetheless, to address the identified separation breaches that present concerns for the DDA procedure, the timing of such sequences was studied in more detail. The average time delay between aircraft reaching 40 nmi to touchdown for the B738 following the E190 for the 8 cases that did not have separation concerns in the DDA procedure is 2 minutes and 10 seconds. The timing delays for the two cases that showed separation concerns were 1 minute and 1 minute and 42 seconds, both of which are shorter delays than the aforementioned average. The data for these cases indicate that the B738 began decelerating earlier in the flight trajectory than the proceeding E190, implying that the implementation of DDA reduces the approach timing of the B738 more significantly than the E190. Holding the succeeding B738 in the specified cases by 10-15 seconds provides adequate separation to match the horizontal separation observed of the baseline.

Conclusion

The implementation of Delayed Deceleration Approach procedures provide environmental benefits including reduced fuel burn and community noise. However, in order to consider the use of DDA on a fleet-wide basis, an understanding of the deceleration rates for a complete fleet of aircraft is necessary. Additionally, a DDA procedure is naturally faster than a conventional landing procedure as a higher velocity is maintained for a longer portion of the landing sequence, which introduces the possibility of a separation breach between succeeding aircraft on the same final approach track. This work evaluated DDA capabilities and environmental benefits for aircraft consuming 83% of the commercial fleet used in 2017 at Boston Logan International Airport and modeled the approach sequences for an average day. The results indicate that performing DDA procedures did not introduce a breach of separation for 97% of sequences studied and reduced fuel burn and exposure to higher airframe noise by an average of 21.5% and 8.8 nmi, respectively. The work presented in this paper provides motivation for the development of decision support tools for employing DDA with ease, in addition to further studying DDA procedures for the remaining aircraft and at a variety of airports in an attempt to determine if there exists limitations for fleet-wide implementation of DDA procedures.

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