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Analyzing & Implementing Delayed Deceleration Approaches

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***Abstract*—Delayed Deceleration Approaches (DDAs) have the potential to be important elements of Optimized Profile Descents to minimize fuel burn and emissions by maintaining airspeed above the initial flap speed for as long as possible during approach. This reduces drag and associated engine power requirements. This paper provides a comprehensive summary of the work performed to analyze this topic over the last few years. First, flight data recorder analysis is presented which shows a 30-50% approach fuel and emissions reduction potential through use of DDAs. Second, analysis of approach procedures at a range of US airports are presented to identify specific opportunities for increased DDA use. Third, a noise study of DDA procedures relative to conventional approach procedures is presented which finds negligible noise impacts. Finally, given the significant benefits potential, airport opportunities and negligible noise impacts determined from these analyses, recommendations to increase the implementation of DDAs using appropriate speed targets on area navigation approach procedures are discussed.**

Keywords-Delayed Deceleration Approach; fuel and emissions reduction; noise impacts; RNAV procedure design.

I. INTRODUCTION

Many studies [e.g., 1-4] have explored the potential for fuel burn, emissions and noise efficiencies in the descent and approach phases of flight through different types of Optimized Profile Descents (OPDs). One technique which has been studied for many years is the Continuous Descent Approach (CDA) [2-5]. CDAs are designed to eliminate level segments present in conventional "step down" approaches, keeping aircraft at higher altitude and lower thrust for longer, thereby reducing noise impacts, as well as fuel burn and emissions. The Delayed Deceleration Approach (DDA) concept is complementary to CDA in that they share an objective to reduce fuel and emissions, but DDA is primarily focused on the *speed* profile whereas a CDA primarily focuses on the *altitude* profile. In practice there is coupling between the altitude and speed profiles (for example an aircraft may only be able to decelerate a given amount during a level altitude segment) and finding the best combination of altitude and speed profiles for a given approach is the ultimate objective to achieve an efficient OPD at any given airport.

There are two fixed speed constraints in most approach operations shown in Figure 1: (1) the terminal area entry speed (e.g., 250 kts at 10,000 ft); and (2) the stabilized final approach speed. There is often significant flexibility the speed profiles between these constraints. It is observed in empirical data that aircraft often decelerate relatively early after entering the terminal, as illustrated by the red region in Figure 1. This can be for a number of reasons, for example air traffic control may command early deceleration to give more time to space and sequence traffic onto the final approach or because of slower traffic ahead in the arrival stream. Earlier deceleration is accompanied by deployment of high-lift devices, requiring higher engine thrust to counteract the resulting higher drag and giving rise to higher approach fuel. This can be avoided by implementing a Delayed Deceleration Approach (DDA) shown by the blue region in Figure 1. The aircraft is kept faster and hence in a cleaner aerodynamic configuration for longer with associated lower fuel burn and emissions due to lower engine thrust requirements. Deceleration to the final approach speed still occurs with sufficient time to comply with current stabilization criteria such that safety is not adversely affected.

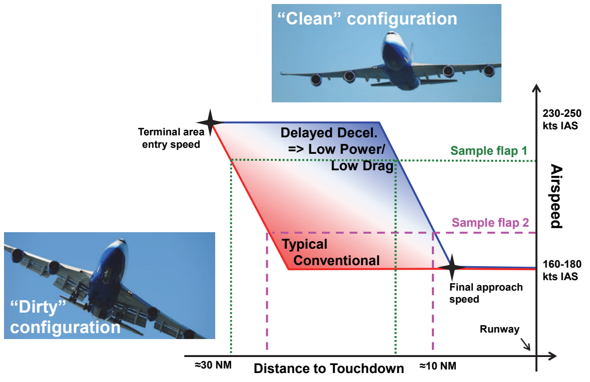

Figure 1. Delayed Deceleration Approach Concept

This paper assesses some of the key potential benefits, challenges and opportunities associated with increased DDA deployment. Section II presents flight data recorder analysis to estimate fuel and emissions savings potential from the DDA concept. Section III analyzes the approach speed deceleration characteristics and their drivers at a range of US airports using radar data. Opportunities and air traffic control challenges of increased DDA concept utilization are discussed based on the results. Section IV summarizes an assessment of noise impacts of DDAs to determine if that could be an impediment to increased utilization. Section V discusses opportunities to implement DDA concepts by leveraging increasing use of area navigation (RNAV) approach procedures. Finally, Section VI presents conclusions and recommendations from this work.

II. DDA FUEL BURN & EMISSIONS REDUCTION POTENTIAL

Data from flight data recorders (FDRs) offers visibility into aircraft state information that is of high value to the analysis of different approach speed profiles, including fuel burn, airspeed, aerodynamic configuration and engine power. FDR data from a set of commercial aircraft operations from a European airline were analyzed in this study, as fully detailed in [6]. Figure 2 presents results from that study in terms of statistical summaries for fuel burn, airspeed, flap angle and engine power for a set of A320 approaches, all flying 3 degree continuous descent approach profiles (to eliminate vertical profiles differences). Similar analyses were also conducted for B757 and B777 aircraft types.

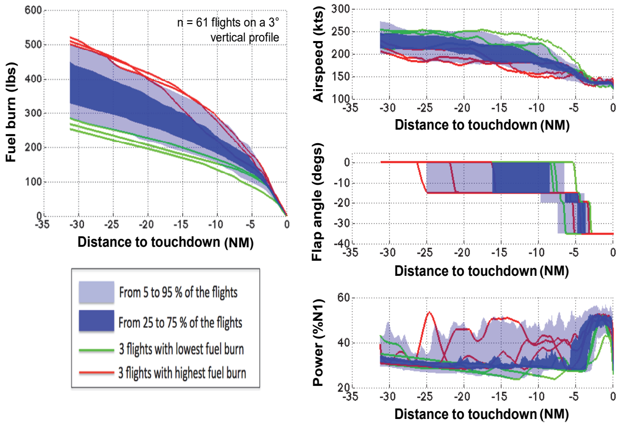

Figure 2. A320 Flight Data Recorder Analysis Results

For each flight parameter from the FDR data, distributions between the different flights were represented in terms of 5th, 25th, 75th and 95th percentiles as a function of distance to touchdown. The 5-95% range shaded in light blue is the zone within which 90% of all the flights fall, while the 25-75% zone shaded in dark blue contains 50% of the flights. In addition, the profiles for the individual flights with the three highest (in red) and the three lowest (in green) fuel burn values are also shown across the different flight parameters.

It is seen that the green flights with the lowest fuel burns were on the "high" side of the airspeed and flap setting profiles (i.e., delaying deceleration and flap deployment until later in the approach, consistent with the DDA concept) and maintained flight idle engine settings until the final approach. The red flights with the highest fuel burn exhibited the opposite characteristics: they decelerated and deployed flaps earlier in the approach and required significantly higher engine power than flight idle. The results from the three aircraft types studied are presented in Table I.

Based on the three aircraft types, this study found a 30-37% fuel burn (and hence carbon dioxide emissions) reduction potential between the average and the latest deceleration profile for flights on three-degree flight path approaches from 10,000ft to touchdown, and approximately a 50% reduction compared to the earliest deceleration profiles averaged across the types.

TABLE I. FLIGHT DATA RECORDER APPROACH ANALYSIS SUMMARY

Aircraft Type	Approach Fuel Burn (10,000 ft to Touchdown)			Fuel Burn Difference (average to lowest)	Fuel Burn Difference (highest to lowest)
	Average of 3 Lowest Fuel Burn Flights	Average of All Flights	Average of 3 Highest Fuel Burn Flights		
A320 (n=61)	268 lbs	383 lbs	509 lbs	-115 lbs (-30%)	-241 lbs (-47%)
B757 (n=64)	377 lbs	597 lbs	869 lbs	-220 lbs (-37%)	-492 lbs (-57%)
B777 (n=16)	727 lbs	1032 lbs	1298 lbs	-306 lbs (-30%)	-571 lbs (-44%)

More analysis was conducted to determine how much of the observed differences were due to airspeed and flap extension differences compared to other operational factors such as wind and aircraft energy variations between flights. Correlation coefficients between a range of potentially relevant parameters were assessed through the calculation of the covariance matrix:

$$R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i)\cdot C(j,j)}} \tag{1}$$

where *R(i,j)* is the correlation coefficient between parameter *i* and *j*, and *C* is the covariance matrix. Figure 3 presents the covariance matrix for the FDR analysis of the three aircraft types studied.

Note that these matrices are symmetric (*R(i,j)=R(j,i)*) so that the lower triangular matrices contain all the information. Following usual rules of thumb with experimental data, correlation coefficients between −0.5 and 0.5 ($R^2 < 0.25$) have been considered poor correlations and are not shown (empty cells in the figure). The coloring of the cells indicates the strength of the correlation (based on the value of R^2) whenever the correlation was deemed significant ($R^2 \geq 0.25$). The sign and value of the correlation coefficient are written in the cell. The higher this value, the stronger was the correlation between the parameter in the row and the parameter in the column. Finally, the grey cells represent variables that were not available from the FDR data for that aircraft type. The first column of each matrix, highlighted by a red box, represents the correlations of the total fuel burn during descent (from 10,000 ft to touchdown) and the other parameters. This analysis shows that for all aircraft types, there is no correlation of fuel burn with spoilers, winds or total energy to a level higher than $R^2=0.25$. This indicates that, despite the variability that exists in these parameters, they have no significant impact on fuel burn. On the other hand, fuel burn proved to be correlated with airspeed with correlation coefficients of −0.6, −0.66 and −0.73 respectively, which is considered a good correlation given the intrinsic variability involved with experimental data. The negative sign indicates that the fuel burn increases as the average airspeed decreases; in other words, early deceleration is accompanied by higher fuel burn.

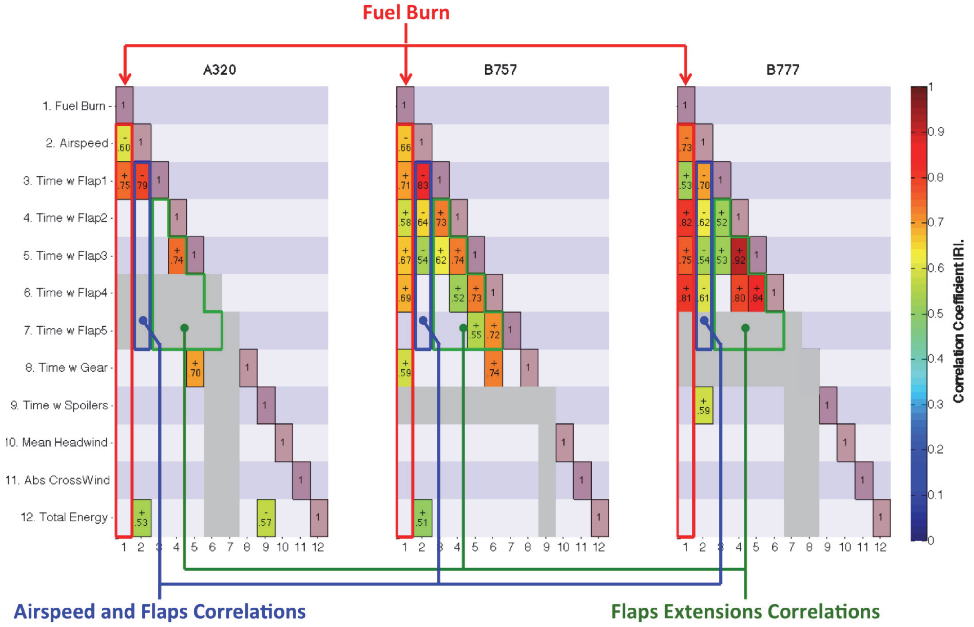

Figure 3. FDR Analysis Correlation Matrices [6]

In addition, fuel burn strongly correlates with time flown with various degrees of flap extended (see blue box), with correlation coefficients higher than R=0.7 for the three aircraft types (the positive sign shows that the more time spent with flaps extended, and the higher the fuel burn). In particular, airspeed strongly correlates with the first flap extension (R=−0.79, R=−0.83, R=−0.7 respectively). Other degrees of flap extensions correlate with airspeed for the B757 and B777, but to a lower extent. The remaining significant correlations are that of total energy (i.e., kinetic and potential) with airspeed for the A320 and the B757, spoiler usage with airspeed for the B777, and total energy with spoiler usage for the A320. The first three correlations are not surprising, since higher total energy may come from higher initial airspeed, which affects the overall airspeed during descent; and spoilers might have been necessary to dissipate high airspeeds. However, the negative correlation of total energy with spoiler usage for the A320 is contrary to the expectation of flights using spoilers to dissipate excess of energy. A further examination of this factor showed that, of the three parameters that affect total energy, it was solely initial altitude that correlated with spoiler usage (the higher the initial altitude in the 10,000 ft ± 1,000 ft range, the lower the usage of spoilers). More details on this are included in [6]. This statistical study showed that fuel burn most strongly correlated with airspeed and time flown with first flaps extended, but no significant correlation (i.e. with $R^2 \geq 0.25$) were found with winds or external energy.

Overall, this analysis points to the potential for significant fuel and emissions savings if more flights adopted a later deceleration speed profile on approach.

III. ANALYZING SPEED PROFILES AT US AIRPORTS

In order to extend this FDR analysis to assess US operations (where FDR data is mostly unavailable for research), speed profiles at a range of US airports have been analyzed using the methodology shown in Figure 4.

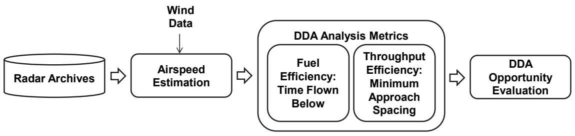

Figure 4. Radar Analysis Methodology

High resolution radar archives were available for nine months of operations from 2011 (Jan-Sep) and eight months from 2015 (Jan-Aug) which contained operations into a range of major US airports. Ground speed estimates contained in the radar archives were converted to airspeed as a function of distance to touchdown using appropriate wind data. Time flown below 180 kts was found to be an effective proxy for fuel burn and first flap deployment for "Large" weight category aircraft [6]. Cumulative distributions of time flown below 180 kts were used as an indicator of approach speed profiles and hence fuel efficiency across a range of airports:

- Capacity-constrained standalone airports (ATL, LAX & BOS)
- New York metroplex airports (EWR, JFK, LGA)
- Washington DC metroplex airports (DCA, IAD, BWI)
- Capacity-unconstrained standalone airports (STL, RIC).

Figure 5 shows sample flight tracks into Atlanta (ATL) airport. The tracks are color-coded by airspeed such that the transition between colors marks the point at which deceleration to 180 kts occurred. It is seen that most tracks decelerate below 180 kts as they turn the base leg onto the final approach path. The cumulative distributions of time flown below 180 kts shown in Figure 6 were calculated based on all approaches in the dataset, separated into Visual Meteorological Conditions (VMC) and Instrument Meteorological Conditions (IMC) at the time of landing. Curves nearer to the top left corner of this space reflect more efficient approach speed profiles (i.e., a larger fraction of operations with a small amount of time spent below 180 kts, implying later decelerations and hence highest fuel efficiency given the results presented in the previous section). At ATL it is seen that 50% of the flights had 2.2 mins or less below 180 kts under VMC, compared to 4.3 mins under IMC, indicating in general flights decelerated much earlier under IMC compared to VMC.

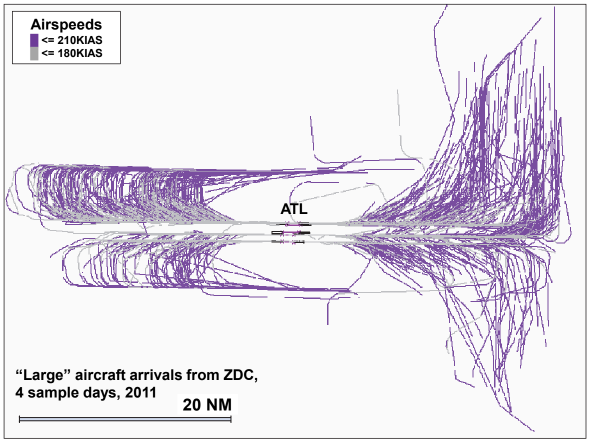

Figure 5. Atlanta (ATL) Flight Track Example

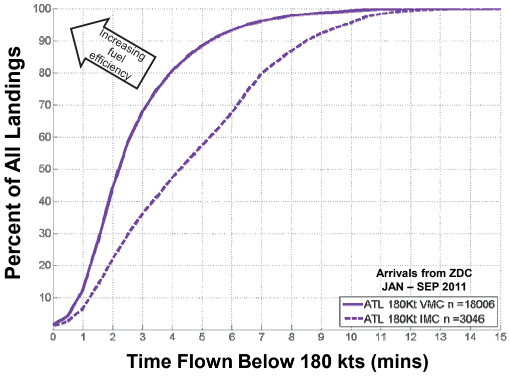

Figure 6. Atlanta (ATL) Time Flown Below 180 kts Cumulative Profiles

Results for the New York metroplex airports are shown in Figures 7 and 8. Earlier decelerations are generally observed under IMC compared to VMC, and that flights at LGA under IMC have earliest decelerations in general. It is likely not a coincidence that LGA has the most restricted airspace (given it is flanked on either wide by EWR and JFK operations) and that capacity is most restricted under IMC. Similar results are seen for DCA airport which is the middle airport in the Washington metroplex. JFK has the least time spent below 180 kts (50% of the flights at 3 mins or less for VMC or IMC) and LGA has the most (at approximately 5 mins under IMC). The similarity between the VMC and IMC curves for JFK indicate their operation is relatively similar under all conditions. This more robust operation possibly reflects their ability to maintain airport capacity under IMC better than some other airports.

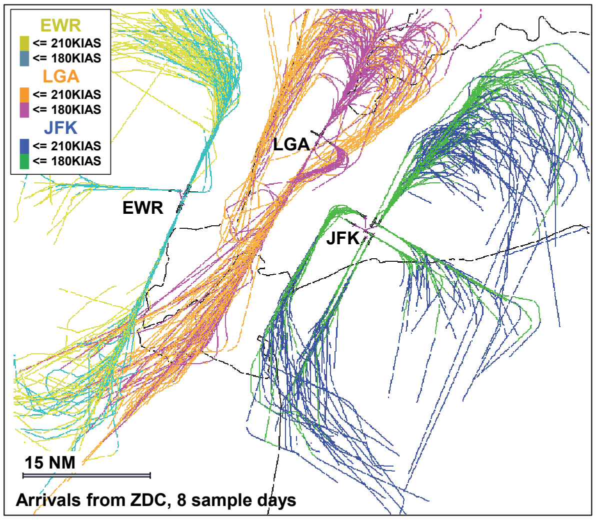

Figure 7. New York Metroplex (EWR, LGA, JFK) Flight Track Examples

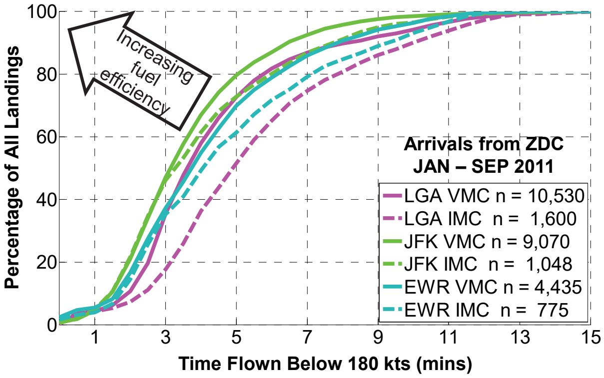

Figure 8. New York Metroplex (EWR, LGA, JFK) Time Flown Below 180 kts Cumulative Profiles

Figure 9 compares the time flown below 180 kts curves for the uncongested standalone airports of St. Louis (STL) and Richmond (RIC). Both of these airports have significantly more airport capacity than demand and are located away from any other large airport. The result is an unconstrained operation and this seems to be reflected in the curves which show late decelerations for a large fraction of operations at these airports.

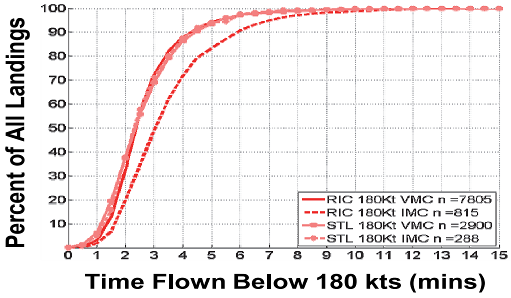

Figure 9. St. Louis (STL) and Richmond (RIC) Time Flown Below 180 kts Cumulative Profiles

Figure 10 compares the time flown below 180 kts for 50% of the flights across all airports for VMC, IMC and the value weighted by the amount of time spent in each condition. These results are from the 2011 data analysis, but similar results were seen from the 2015 data too. The dashed line represents the benchmark performance of STL to make it easier to visualize the reduction in time spent below 180 kts needed at other airports to match the STL existence case. It is seen that the two capacity-unconstrained standalone airports studied have the lowest time flown below 180 kts (i.e., most consistent with the DDA philosophy), while the two most constrained of the metroplex airports studied have the longest time flown below 180 kts (i.e., least consistent with the DDA philosophy). It is hypothesized that the more constrained the airspace, the greater the need for earlier decelerations to manage controller and pilot workload associated with spacing and sequencing arriving traffic and executing approach operations respectively. Later sections will discuss how advanced procedures and automation may be able to mitigate some of these issues to enable increased use of more efficient speed profiles.

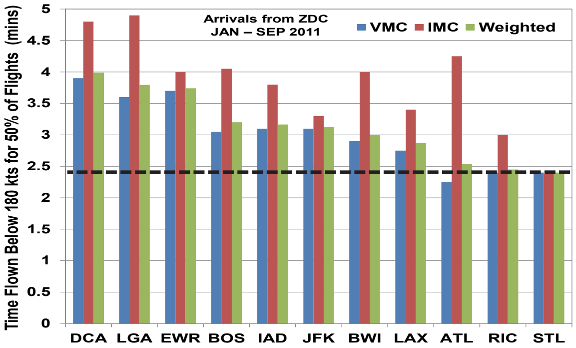

Figure 10. Comparison of Airport Performance of Time Flown Below 180 kts Achieved by 50% of Flights, 2011 data

In order to better understand the differences in speed profile characteristics between airports, a methodology was developed to identify some of the drivers. If the primary drivers of speed behavior at a given airport can be modified to encourage greater DDA usage (for example through modified pilot or controller training) they would be good targets for further study. It will be more difficult to increase the utilization of DDA-type procedures at airports where the primary drivers are based on elements such as airspace or airport constraints. A classification tree approach was taken which predicts the importance of key input variables on the metric of interest. A tree is "grown" which identifies which combination of independent variables best correlates with the dependent variable that appears at the "leaf" of the tree. In general, the earlier the split occurs in the tree, the more important the independent variable is in impacting the dependent variable. The path from the root to the leaf represents the combination of independent variables which lead to a given dependent variable. In this case, the independent variable of interest is the time flown below 180 kts, and the independent variables selected were weather (VMC or IMC); hourly Airport Acceptance Rate (AAR); total arrival demand; airport configuration and airline. Example results from application of this approach at ATL and JFK are presented in Figure 11.

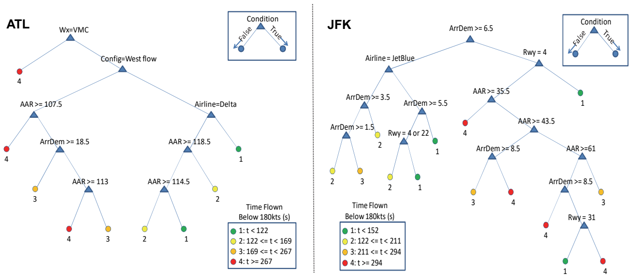

Figure 11. ATL and JFK Approach Speed Profile Classification Trees

A full discussion of the approach and results can be found in [7]. In these results, weather condition is the main variable at ATL, while arrival demand is the key driver at JFK, indicating some influences vary by airport. However, other variables were seen to be important across airports. For example, airport configuration and dominant carrier appear as high impact variables at both airports shown in Figure 11. The dominant carrier influence suggests airline standard operating procedures may play an important role in approach speed profiles and this is an area to target in stakeholder outreach activities to encourage greater use of DDAs when/where appropriate.

IV. DDA NOISE ANALYSIS

The previous sections have shown that DDA procedures hold potential for significant fuel and emissions savings, but there are various operational impediments to their increased use, including airspace constraints and controller and pilot technique, especially during high demand periods. An additional impediment that needs to be understood is the impact on noise levels of modified approach speed profiles. The changes involved in a DDA, including modified airspeed, aircraft configuration (e.g., flap deployment) and engine thrust as a function of distance to touchdown have an effect on noise levels. The procedure typically result in lower engine thrust settings (and hence lower engine noise) but higher airspeeds (and hence higher clean airframe noise) early in the approach, but potentially slightly higher engine thrust, flap noise and greater spoiler usage later in the approach. Therefore, a noise study was conducted to (1) gather empirical noise data to better understand the correlation of noise impacts on the ground with airspeed and aerodynamic configuration for a range of aircraft types; and (2) develop and apply a noise modeling approach to assess noise impacts as a function of approach speed and hence determine implications of noise assessment for increased DDA deployment. Full details of this noise analysis can be found in [8], but the main findings are summarized below.

A. Empirical Noise Measurement Activities

The goal of the noise measurement campaign was to correlate noise measurements on the ground in targeted locations with aircraft surveillance track data in order to determine the relationships between noise, airspeed and configuration for a range of approach procedures and aircraft types. Through post-event analysis, flights could be characterized as decelerating relatively earlier or later in the approach and hence the net noise impact of DDA operations could be estimated.

Noise monitors were deployed at key locations around Boston Logan International Airport (BOS) given its potential for benefit from DDA procedures (established in the analysis above), and its proximity to the research team which facilitated the noise data collection activity. Monitors were located at approximately 13, 16 and 20 NM from touchdown for flights on the RNAV arrival path from the north to runway 22L/R at BOS (one of the dominant arrival configurations at the airport) and measurements taken for a 10 week period from November 2015 through January 2016. The monitors collected 1-second equivalent sound level (L_{eq}) noise data. Flight track radar data was used to correlate a noise event to a specific aircraft and to determine its altitude and speed as it overflew the monitor. The groundspeed of the aircraft was calculated based on radar position information as a function of time, and this was converted to airspeed using a wind vector determined from the North American Regional Reanalysis (NARR) data interpolated in space and time to the aircraft position. The L_{eq} noise data was converted into peak noise (L_{max}) and Sound Exposure Level (SEL) metrics.

After normalizing all the collected noise values, the results were divided into subsets based on aircraft type. The three aircraft types with the most data were the A320, B737 and E190. Results of the SEL noise metric for these three types are presented in Figure 12 for two of the monitors. The results do not show a noticeable relationship between airspeed and SEL. By fitting a line to these data clusters, there is a slightly negative slope indicating a small decrease in noise with increasing airspeed. Similar results were found for the L_{max} metric.

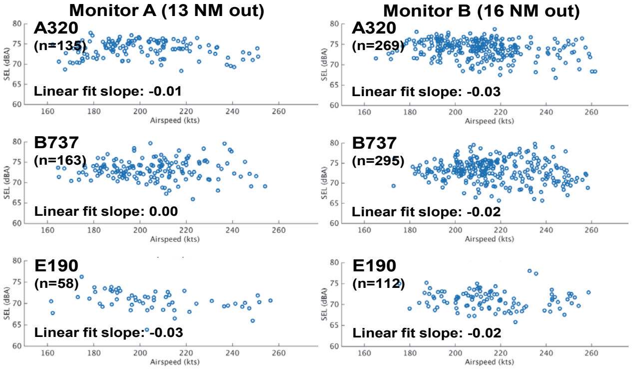

Figure 12. SEL Airspeed Comparison by Monitor Location & Aircraft Type

To see if there was any noticeable difference between those aircraft that were flying profiles with relatively early or late deceleration compared to average, the average speeds of the flights using the full RNAV approach were calculated from 40 NM track distance to the runway. On average, SEL of the later decelerating flights were found to be 1-2 dB less than those with early deceleration. But given the variability in the data, no statistically significant correlations were observed in any of the empirical data.

B. *Noise Modeling Activities*

The standard technique for evaluating noise from new flight procedures is through Noise Power Distance (NPD) relationships, as used by the FAA's Integrated Noise Model (INM), Aviation Environmental Design Tool (AEDT), and some third-party noise evaluation software. In the NPD approach, the aircraft and flight procedure to be evaluated are matched with the thrust levels and configuration from flight test data. Noise levels are then interpolated as a function of observer distance, assuming a standard atmosphere and consistent sound energy dissipation with distance [9]. Limitations of this method are that it requires interpolation of a small set of thrust levels and configurations such that the detailed noise effects from new variations in operational procedures or new aircraft cannot be captured. In addition, it models noise attenuation based simply on distance from a single source, when in reality noise propagation depends on aircraft configuration, attitude, and specific sources of noise. Therefore, the fidelity is too low to capture the effects of new operational procedures, especially those which modify the aerodynamic configuration of the aircraft such as in the DDA concept.

To address these limitations, higher-fidelity physics-based models can be used to capture various noise sources, shielding, and propagation. The outputs of such models can be used as a stand-alone for noise analysis or be converted into NPD data sets with a better representation of aircraft configuration, speed, and thrust levels of interest. The Aircraft NOise Prediction Program (ANOPP) is one model that can be used for this purpose. ANOPP is a NASA developed semi-empirical model that computes noise levels from the airframe and engine components (i.e., fan, core, jet, and turbine) at a user-defined observer grid for a user-defined flight procedure [10]. It also accounts for propagation through user-defined atmosphere and shielding effects.

To use the model, the user must also input aircraft and engine component geometry and performance parameters for the existing or new aircraft being evaluated. The Transport Aircraft System OPTimization (TASOPT) [11] can be used to supply the performance parameters ANOPP requires. This tool jointly optimizes the airframe, engine, and full flight trajectory of a "tube and wing" transport aircraft using physics-based computations, and is therefore useful for predicting weight, aerodynamics and performance without the need for traditional empirical drag and weight prediction methods. A tool to translate the performance outputs from TASOPT into inputs for ANOPP has been created at MIT and is illustrated in Figure 13.

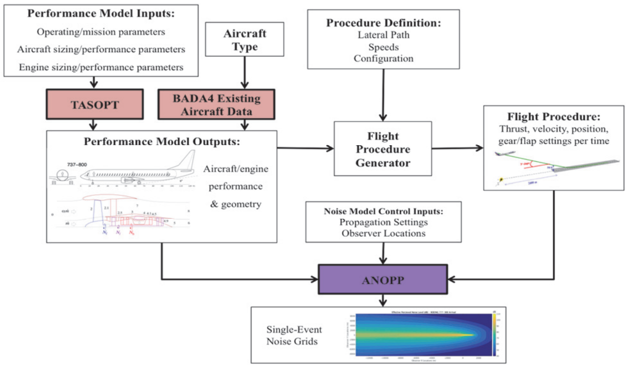

Figure 13. Schematic of TASOPT to ANOPP Integration Process

Along with the outputs from TASOPT, the observer grid and propagation settings (e.g., atmosphere definition, consider shielding effects or not, etc.) and the flight procedure thrust, velocity, and position profiles as a function of time must also be supplied. A generator was created to compute the specifics of a flight procedure using a basic force-balance model to determine required thrust levels given a user-specified flight-path angle and velocity. The Base of Aircraft Data (BADA) Family 4 [12] provides the fuel burn model basis. To verify the accuracy of this integrated system, results have been compared to FAA certification noise data at the standard "flyover", "approach" and "sideline" locations along with weight, configuration and thrust levels for many aircraft types. Comparison between the measured and modeled L_{max} values were within 7 dBA agreement across all cases, i.e., well within the scatter seen in the measured data.

Next, the model was used to assess the noise impacts of modifying the speed profile on a representative approach profile observed during the measurement campaign. The top panels of Figure 14 show the altitude profile based on the selected flight, together with the early and late deceleration profiles and the resulting thrust profiles determined with the model described above. The bottom panels show the calculated difference between the SEL noise contours from the early and late deceleration profiles, with red colors indicating the late deceleration case is louder, and blue colors indicating it is quieter. It is seen that the *total* noise impact differences between the two profiles are generally small, with slightly louder noise from the late deceleration case directly under the approach path at the start of the downwind leg and around the landing gear deployment location, but slightly quieter elsewhere. The lower right results break out the total noise difference into airframe and engine noise components, where it is observed that in general the airframe noise is higher with the later deceleration (as expected given the higher speed airflow over the airframe) while engine noise is lower (as expected given the lower thrust levels needed for the approach). These effects largely offset leading to the small differences observed in the total noise contour in the lower left.

In summary, neither the empirical study nor the noise modeling test cases have shown significant positive or negative impact on noise from DDA operations outside the range of the scatter in the measured data.

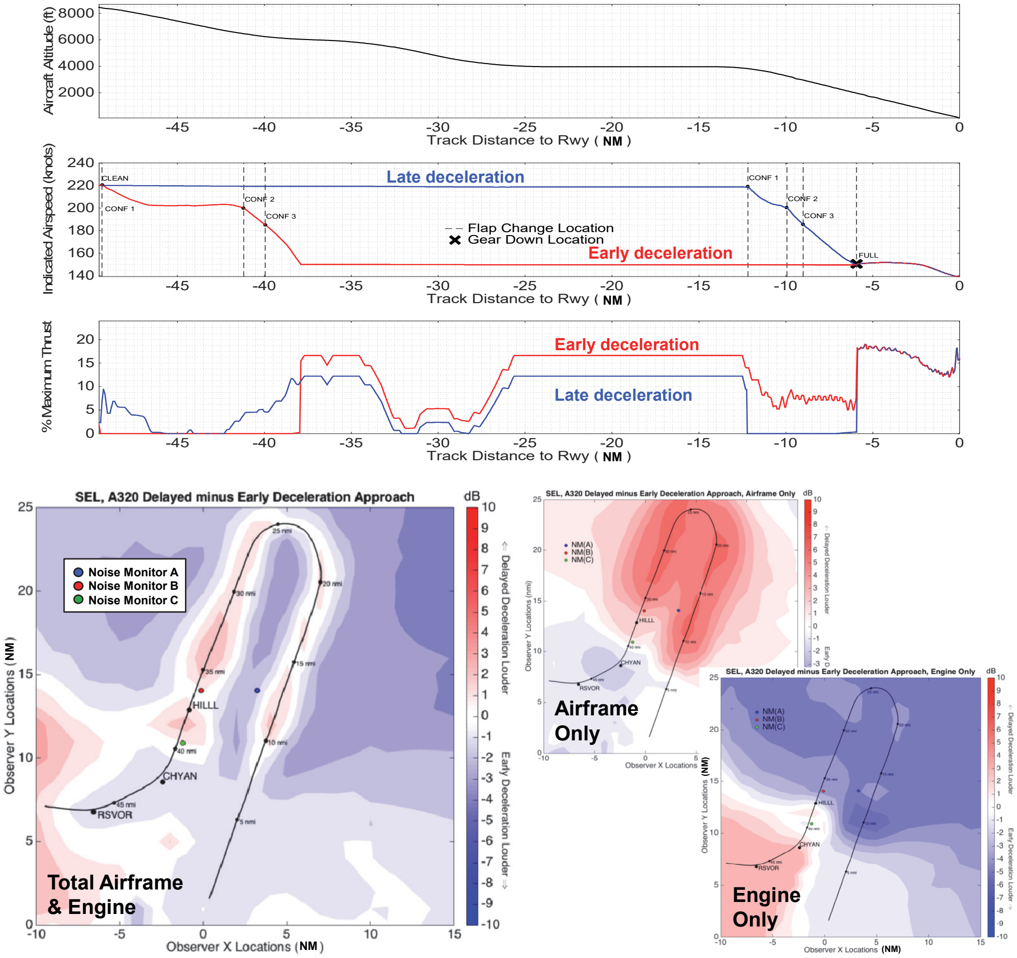

Figure 14. Modeled SEL of BOS Approach with Early and Late Deceleration Speed Profiles

V. RNAV DDA PROCEDURE OPPORTUNITIES

One of the biggest uncertainties in effective implementation of DDAs during vectoring operations is the uncertainty in track distance to fly until touchdown. To mitigate this barrier, RNAV approach procedures can be developed with appropriate speed targets at waypoints which are a known track distance from touchdown. This is considered an especially attractive technique to encourage greater DDA utilization as it leverages existing NextGen and SESAR investments in RNAV procedure design, but with appropriate speed targets overlaid on them. These procedures can be executed by a Flight Management System (FMS) available on most modern commercial aircraft. This section discusses simulation studies to explore relevant fuel saving potential and procedure design aspects.

A. Fuel Saving Potential from RNAV DDAs

A simulation system has been created at Lincoln with collaboration from Honeywell which couples the actual Pegasus FMS logic with an FDR-validated commercial-grade simulation of a B757-200 aircraft. More details of this system can be found in [13]. This allows flight characteristics and fuel burn to be estimated for RNAV procedures with different speed targets.

Results for three approaches with different speed targets built around the ATL DIRTY RNAV Standard Terminal Arrival Route (STAR) for runway 26R are presented at the top of Figure 15. The speed targets applied at various points along the approach forced different deceleration profiles ranging from early deceleration, through an "average" speed profile, to late deceleration. All lateral and vertical components of the published procedure were left unchanged. Simulations were started with aircraft 135 NM track distance away from the runway, en route at FL340 and with a gross weight of 190,000 lbs. Data were analyzed for each scenario from the point where the aircraft's track crossed the TRACON boundary until the aircraft descended to 50 ft Above Ground Level (AGL), a distance of approximately 40 NM.

The resulting fuel burn differences for the various speed profiles at a range of landing weights are shown in the bottom panel side of Figure 15. It is seen that the late deceleration case (Scenario 1) burnt 54% less fuel than the early deceleration case (Scenario 3) and 31% less than the medium deceleration case (Scenario 2). The values are consistent with the fuel saving potential suggested in the FDR data analysis reported earlier. Sensitivity of the fuel burn results to aircraft weight show that large changes in aircraft weight can have meaningful effects on fuel consumption. The greatest effect of weight is associated with the early deceleration scenario.

B. Design Considerations for RNAV DDA Procedures

The previous analysis demonstrated that it was feasible to realize significant fuel benefits from operationally-realistic FMSs on a single aircraft type by using tailored speed targets.

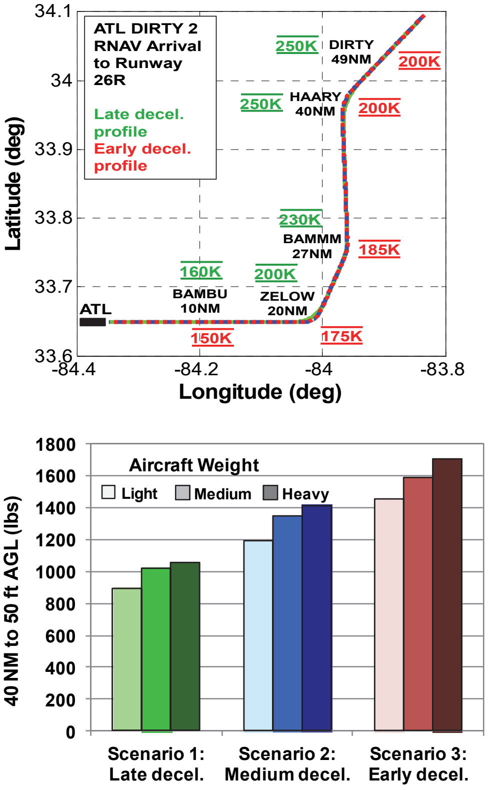

Figure 15. Simulated ATL Approach Procedure, Speed Targets & Associated Fuel Burns

But in order for such approaches to be practical at any given airport, procedures need to be tuned to minimally modify existing procedures and to be flyable by a range of aircraft types which make up the fleet. The aircraft modeling system shown in Figure 13 was leveraged to evaluate the speed envelopes for a range of representative aircraft types. For example, Figure 16 shows the latest deceleration profiles for a set of representative aircraft types for a simple flight idle, three degree continuous descent approach profile.

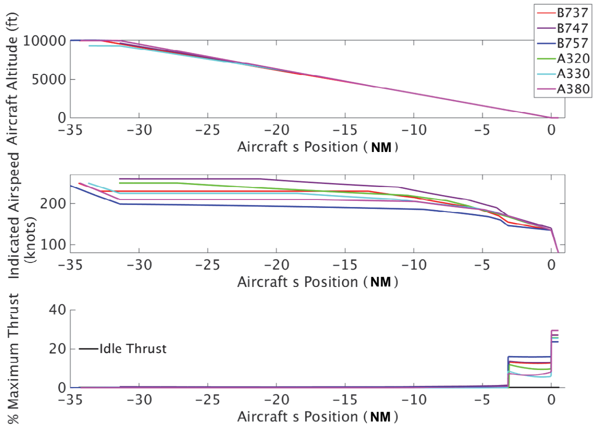

Figure 16. Latest Deceleration Speed Envelopes for Representative Aircraft Types on Flight Idle Continuous Descent Approach Profile

These results highlight that some aircraft types (e.g., B757) require much longer distances to decelerate compared to others on this profile. As a result, RNAV DDA speed targets tuned to the average aircraft capabilities will not be flyable by the types that need longer to decelerate, but procedures designed to be flyable by all types would be sub-optimal for the types capable of decelerating much later, resulting in lower benefits realized. One technique to enable aircraft that need longer distances to decelerate to be integrated into arrival flows with other types is to expect use of spoilers. However, discussions with pilots and air traffic controllers have indicated this would be undesirable for routine operation.

C. *Assessing RNAV Procedure Speed Targets*

In order to assess the state of existing RNAV procedure speed targets against DDA characteristics, further analysis was conducted. The ROBUC2 approach procedure to runway 4 at BOS was selected for initial study as it had multiple speed constraints (e.g., 210 kts at 6000 ft and 220 kts at 9000 ft). The BADA4-based performance model described above was used to compare the fuel burns between approaches of A320, B737 and B757 with lateral and vertical profiles as published in the procedure, but with a range of speed profiles. These were: (1) an "empirical early" speed profile observed for that approach path in the analysis from Section III; (2) the speed profile fully compliant with the published procedure; (3) the latest deceleration profile flyable without spoilers by the B757 (i.e., the type requiring the earliest deceleration from Figure 16); and (4) the latest deceleration profile flyable without spoilers by each type modeled. The results are presented in Figure 17. It is seen that, relative to the published procedure (blue bars), the empirical early profile results in significantly higher fuel burns from the ROBUC fix (approximately 50 NM out) to touchdown (red bars). If the ROBUC2 speed constraints are removed, it is seen that some additional fuel burn reductions are possible going to the latest profile flyable by the B757 (yellow bars) for B757 and B777 types, but not the A320 and B737. Significant fuel burn reductions would be enabled by allowing each type to fly its latest deceleration profile (green bars). These would be unrealistic from an operational perspective given every aircraft type in the arrival stream would have a different approach speed profile, but it illustrates the theoretical fuel reduction benefits pool.

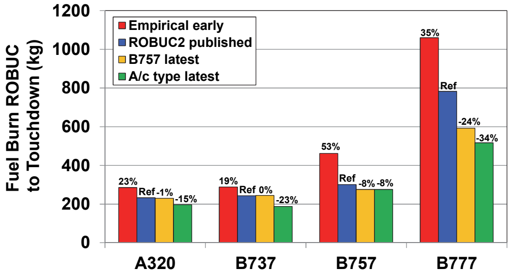

Figure 17. BOS ROBUC2 Fuel Burns with Different Speed Profiles

In order to assess different published RNAV procedure speed targets relative to the DDA concept, Figure 18 compares speed profiles that are fully compliant with the speed targets in the published procedure (solid line) to the latest deceleration profile flyable by the B757 without spoilers (dashed line) for several BOS and CLT procedures. Because the generic DDA profile must accommodate aircraft with the slowest deceleration rates (i.e., lowest drag), the B757 was again used as the reference in this analysis given the results in Figure 16 to ensure the tested profiles were flyable by most types. The lateral and vertical profiles were as published in all cases. How close the solid and dashed lines are in each case reflect how close the published procedure gets to the latest deceleration profile flyable by the B757. The lines for the BOS procedures are close together, while the CLT FILPZ procedure to 36L forces much earlier deceleration than even the B757 requires. So this procedure may be a candidate for speed target modification if ATC procedures and airspace restrictions allow.

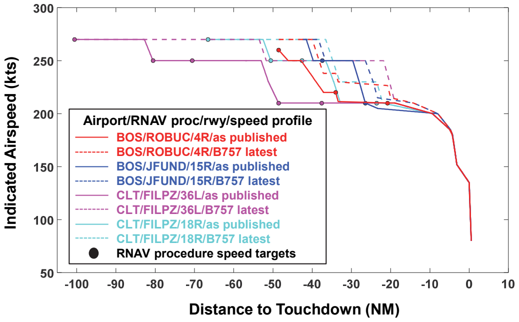

Figure 18. B757 Speed Profile Comparisons Between RNAV Target Compliant (solid) & Latest Deceleration (dashed)
(Coding: Airport/RNAV proc/Runway/Spd profile)

In order to quantify the differences between these lines, Figure 19 compares the area between them (bar colors consistent with lines in Figure 18) and several other airports/procedures (grey bars). This "area comparison" methodology is proposed as an effective screening tool for assessing the opportunities for speed target modification of existing RNAV approach procedures, or to be used during the design of new procedures to ensure consideration of efficient speed profiles. The larger the area, the larger the opportunity for modifying the speed targets on the procedure to promote more fuel efficient speed profiles if other constraints allow. Note, in Figure 19, the impact downwind segments can have. For example, there is a large efficiency difference between the CLT/FILPZ/36L short and long downwind case.

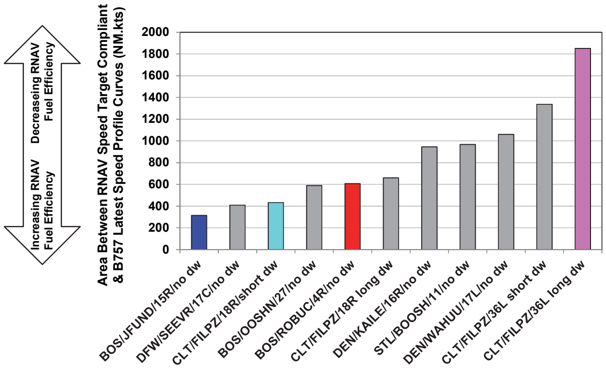

Figure 19. Area Comparison Between RNAV Speed Target Compliant & B757 Latest Deceleration Speed Profiles (Coding: Airport/RNAV procedure/Runway/Downwind length)

VI. CONCLUSIONS AND RECOMMENDATIONS

Delayed Deceleration Approaches offer potential for reduced fuel burn by maintaining airspeed above the initial flap speed for as long as possible during approach. Analysis suggests 30-50% fuel and emissions reductions can be achieved during approach by employing DDA, but that the majority of flights decelerate much earlier in current operations at major US airports. Extensive radar data analysis for a range of airports has provided insights into which airports (and operating conditions at those airports) could theoretically benefit most from increased DDA usage. In practice, there are barriers to implementation which may prevent increased DDA usage at some locations. A classification tree approach has been presented to illustrate how barriers can be identified so mitigations can be explored. A noise analysis has shown there is a negligible effect of the DDA concept on noise impacts on the ground. Finally, it has been shown that RNAV arrival procedures can be leveraged to facilitate increased usage of DDA procedures. A screening method has been introduced which can be used to identify opportunities for speed target modifications on existing RNAV procedures to further promote DDA concepts.

Recommended next steps include promoting the concept and potential benefits to appropriate stakeholders (e.g., airlines, ATC facilities and RNAV procedure designers). Because the DDA concept will modify flight crew and ATC procedures during approach operations, human factors assessments of workload and other operational acceptability criteria are likely to be required before any procedure modifications can be made. Leveraging emerging automation concepts such as the NASA/FAA Terminal Sequencing and Spacing (TSS) system to facilitate the execution of appropriate delayed deceleration speed profiles is another implementation opportunity that should be explored.

DISCLAIMERS

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EUROCONTROL holds rights to the BADA4 model.

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REFERENCES

[1] Knorr, D., X. Chen, M. Rose, J. Gulding, P. Enaud & H. Hegendoerfer, "Estimating ATM Efficiency Pools in the Descent Phase of Flight", *9th USA/Europe Air Traffic Management Research and Development Seminar (ATM 2011)*, Berlin, Germany, 2011.

[2] Clarke J-P, N. Ho, L. Ren, J. Brown, K. Elmer, K.-O. Tong & J. Wat, "Continuous Descent Approach: Design and Flight Test for Louisville International Airport", *Journal of Aircraft*, Vol. 41, No. 5, pp.1054-1066, 2004.

[3] Shresta S., D. Neskovic & S. S. Williams, "Analysis of Continuous Descent Benefits and Impacts During Daytime Operations", *8th USA/Europe Air Traffic Management Research and Development Seminar (ATM 2009)*, Berlin, Germany, 2011.

[4] Alam, S., M. H. Nguyen, H. A. Abbass, C. Lokan, M. Ellejmi & S. Kirby, "A Dynamic Continuous Descent Approach Methodology for Low Noise and Emission", *29th IEEE/AIAA Digital Avionics Systems Conference*, 2010.

[5] Reynolds, T. G., L. Ren & J-P. B. Clarke, "Advanced Noise Abatement Approach Activities at a Regional UK Airport", *Air Traffic Control Quarterly*, Vol. 15, No. 4, pp. 275-298, 2007.

[6] Dumont, J-M., "Fuel Burn Reduction Potential from Delayed Deceleration Approaches", *Master's thesis submitted to the Department of Aeronautics and Astronautics*, Massachusetts Institute of Technology, http://hdl.handle.net/1721.1/77108, 2012.

[7] Reynolds, T. G., Y. Rodriguez, M. McPartland, M. Sandberg, J-M. Dumont & R. J. Hansman, "Assessment of Delayed Deceleration Approach Opportunities at US Airports", *15th AIAA Aviation Technology, Integration and Operations Conference*, Dallas, TX, AIAA 2015-2433, 2015.

[8] Sandberg, M., T. G. Reynolds, J. Thomas & R. J. Hansman, "Delayed Deceleration Approach Noise Assessment", *16th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2016-3907, Washington DC, 2016.

[9] Boeker, E., *et al.*, "Integrated Noise Model (INM) Version 7.0 Technical Manual", U.S. Department of Transportation Research and Innovative Technology Administration, Cambridge, 2008.

[10] Rawls, C. & J. Burley, "Aircraft Noise Prediction Program (ANOPP) Technical Manual", NASA Langley Research Center, Hampton, 2012.

[11] Drela, M., "Transport Aircraft System OPTimization, Technical Description", Massachusetts Institute of Technology, 2011.

[12] Nuic, A. & V. Mouillet, "User Manual for the Base of Aircraft Data (BADA) Family 4", EUROCONTROL, EEC Technical/Scientific Report 12/11/22-58, 2012.

[13] Jones, J., M. McPartland, T. Reynolds, Y. Glina, C. Edwards & S. Troxel, "Methods of Selecting Forecast Winds for Flight Management Systems to Support Four Dimensional Trajectory-Based Operations", *16th AIAA Aviation Technology, Integration, and Operations Conference*, AIAA Paper 2016-4069, Washington DC, 2016.

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