

# Fuel Burn and Emissions Reduction Potential of Low Power/Low Drag Approaches

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Changing aircraft operational procedures is one strategy that can be used to reduce fuel burn and mitigate environmental impacts of aviation in relatively short timeframes with existing aircraft types. This study quantifies the fuel burn and emissions reduction potential of delayed deceleration approaches, where the aircraft is kept fast and in clean aerodynamic configuration for as long as possible during the approach phase of flight. This reduces the drag and thrust requirements and these procedures are therefore called Low Power/Low Drag approaches. Operational data is used to characterize approach profiles, together with their fuel burn and emissions properties correlated to airspeed and configuration for a selection of aircraft types. Aircraft that were observed to decelerate and configure flaps later in the approach had 30-40% lower fuel burn and carbon dioxide emissions below 10,000 ft compared to those that did not. Estimates of US system-wide fuel burn and emissions reduction potential from Low Power/Low Drag approaches are provided: if only 1% of the total operations used these approaches, savings across all operators would amount to 2.9 million US gallons (\$5.8-11.6 million at \$2-4/US gallon) of fuel and 28,000 metric tons of carbon dioxide emissions per year. A discussion is provided on the implementation barriers which need to be addressed if benefits are to be realized.

## I. Introduction

Various strategies are being pursued to reduce fuel burn and mitigate the environmental impacts from aviation, including developing advanced aircraft technologies and sustainable alternative jet fuels; creating new policies and standards; and modifying operational procedures. Operational changes have smaller overall mitigation potential compared to the other options, but can be implemented in much shorter timeframes with existing aircraft types. A comprehensive identification and systematic evaluation of potential near-term operational changes has been conducted to determine their relative environmental mitigation benefits, as well as other factors such as barriers to implementation [1]. This was used to identify promising mitigations for further study and possible near-term implementation: one mitigation identified in this way was the wider use of delayed deceleration leading to Low Power/Low Drag (LP/LD) approaches.

Figure 1 presents a conceptual comparison between the airspeed profiles for a delayed deceleration LP/LD and a conventional approach. In this simplified view, there are two airspeed constraints in the terminal area: the entry airspeed (often governed by letters of agreement between the En Route Centers and terminal area control (TRACON), or the 250 knot speed limit below 10,000ft) and the final approach stabilization speed. TRACON controllers and flight crews have some flexibility in speed profiles between these two constraints. In typical conventional approach operations, aircraft often decelerate relatively early in their approach trajectory. This can be for a number of reasons, for example air traffic control may command early deceleration to give

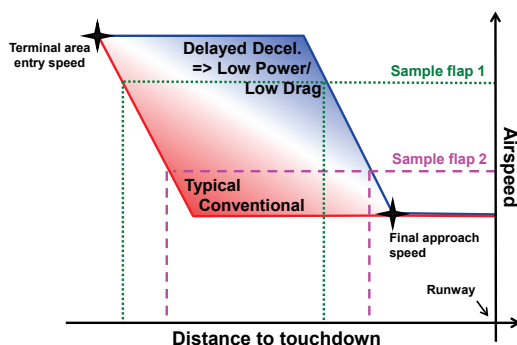


Figure 1: Comparison of Low Power/Low Drag and Conventional Airspeed Profiles

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more time to space and sequence traffic flows onto the final approach. Earlier deceleration is accompanied by earlier deployment of high-lift devices such as flaps to maintain airplane maneuverability and stall speed limits. The resulting increase in drag leads to higher engine thrust, thus giving rise to higher approach fuel burn, emissions and engine noise. This can be avoided by delaying the deceleration to implement an LP/LD approach where the aircraft speed is kept higher for longer during the initial stages of the approach, resulting in a cleaner aerodynamic configuration with associated lower fuel burn and emissions due to lower engine thrust requirements. Flap deployment and deceleration to the stabilized final approach speed occur later in the approach. This LP/LD philosophy is complementary to the widely-studied Continuous Descent Approach (CDA) procedure (e.g. [2,3]) in that the LP/LD focus is on the approach speed profile while the CDA primary focus is on the approach vertical profile. However, LP/LD has not been studied in as much detail as CDA and therefore the study reported in this paper is designed to assess the fuel burn and emissions reduction potential of LP/LD approaches. In practice, there is a range of airspeed profiles within the envelope defined by the worst-case conventional profile (where deceleration to final approach speed occurs immediately upon entry into the terminal area) and the best-case delayed deceleration LP/LD profile (where deceleration to final approach speed occurs at the last possible moment), as shown in Figure 1. This study uses flight data recorder (FDR) data to characterize the range of approach profiles observed in the current operational environment, and correlates their fuel burn and emissions properties to establish first-order estimates of fuel burn and emissions impacts of profiles which are closer to the LP/LD ideal. The methodology being followed to achieve this objective is described in the next section, followed by analysis results for a representative set of aircraft types. Estimates of US system-wide fuel burn and emissions reduction potential from Low Power/Low Drag approaches are then provided, as well as a discussion of implementation barriers.

## II. Assessment Methodology

The assessment methodology used in this work is shown in Figure 2. Archived FDR data covering several thousand flights were acquired from a major European airline for a range of aircraft types. Three types were analyzed which were representative of the different sizes of aircraft within the US fleet: a small narrowbody (Airbus A320); a large narrowbody (Boeing B757) and a two engine widebody (Boeing B777).

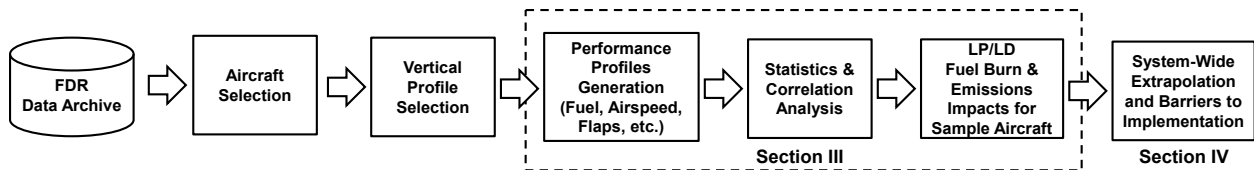


Figure 2: Low Power/Low Drag Assessment Methodology

Analysis was limited to flights on approximate three degree descent profiles from 10,000 ft to touchdown (ground distance cut-off of 31.4 nm, corresponding to 10,000 ft on a three degree glide path), as illustrated in Figure 3. The tolerances for upper and lower boundaries around the three degree profile were  $\pm 1,000$  ft respectively. Not only did this vertical profile definition eliminate flights that had approach profiles with terminal holding typically not seen in the US, but it also meant the analysis was conducted on flights following approximate CDA vertical profiles. Therefore, the key difference between the flights analyzed was in their speed and flap configuration profiles, allowing the main impacts of interest to an LP/LD assessment to be isolated. The fact that all flights were conducting near-CDA profiles also meant that any fuel burn and

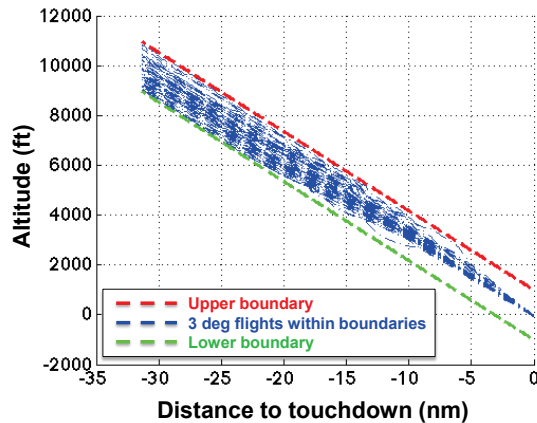


Figure 3: Definition of Three Degree Approach Path

emissions differences observed due to LP/LD speed profiles were likely to be a lower bound compared to if the vertical profile constraint was relaxed. Performance profiles in terms of fuel burn, airspeed, flap, gear and thrust as a function of distance to touchdown were extracted for all flights meeting the aircraft type and vertical profile selection criteria. Statistical distributions of the performance metrics could then be determined, along with statistical correlations between fuel burn and the other performance metrics. From this, fuel burn and emissions benefits of LP/LD approaches could be estimated for the sample aircraft. Key results from this process are discussed in Section III. Extrapolation of findings and consideration of barriers to implementation across numerous airports is required in order to assess the system-wide environmental impact reduction potential of LP/LD procedures which is the overall objective of this study. This is discussed in Section IV.

### III. Flight Data Recorder Analysis and Results

#### A. Analysis Approach

The FDR archives available for this analysis included numerous parameters (approximately 100, the exact number depending on the aircraft type) recorded at 10 second intervals (initial approach) or 1 second intervals (final approach). The key parameters of interest in this study were fuel burn (obtained from the integration of fuel flow over time); airspeed; flap angle; landing gear position; engine power level (in terms of fan rotation speed (%N1)); altitude; mass (inferred by the Flight Management System (FMS) given known pre-flight load information); and wind field (inferred by the FMS given differences between the air and ground tracks).

For each flight in the archive that met the aircraft type and altitude profile criteria discussed above, profiles of the key parameters were analyzed as a function of distance to touchdown for the period the flights were within a typical terminal area: the focus was on the phase from 10,000 ft to the runway in this analysis. An example set of fuel burn profiles for the A320 is shown on the left side of Figure 4. These plots represent how much fuel was burnt from 10,000 ft to touchdown as a function of distance to the runway; the first value is therefore the total cumulative fuel burn during approach. Statistical properties of the set of profiles were also calculated in terms of 5%, 25%, 75% and 95% percentiles as a function of distance to touchdown, as illustrated for the same data on the right side of Figure 4. These statistical parameters provide important insights into the distribution of flights: 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. The middle of this latter area is therefore representative of the average profile.

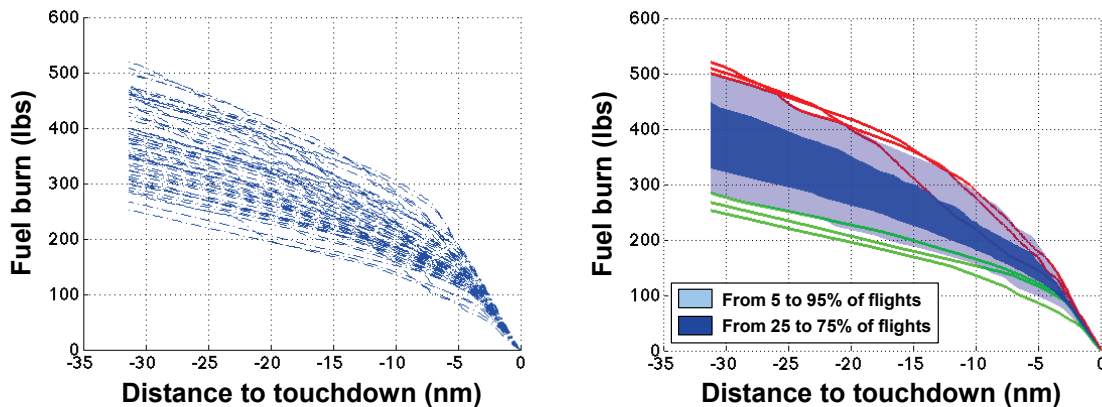


Figure 4: Sample A320 Fuel Burn Profiles (left) and Statistical Summary (right)

#### B. FDR Analysis Results by Aircraft Type

Statistical summaries for fuel burn, airspeed, flap angle and engine power are presented for each representative aircraft type: the A320 in Figure 5, the B757 in Figure 6 and B777 in Figure 7. For each parameter, the specific profiles for the flights with the three highest (in red) and the three lowest (in green) fuel burns are also shown.

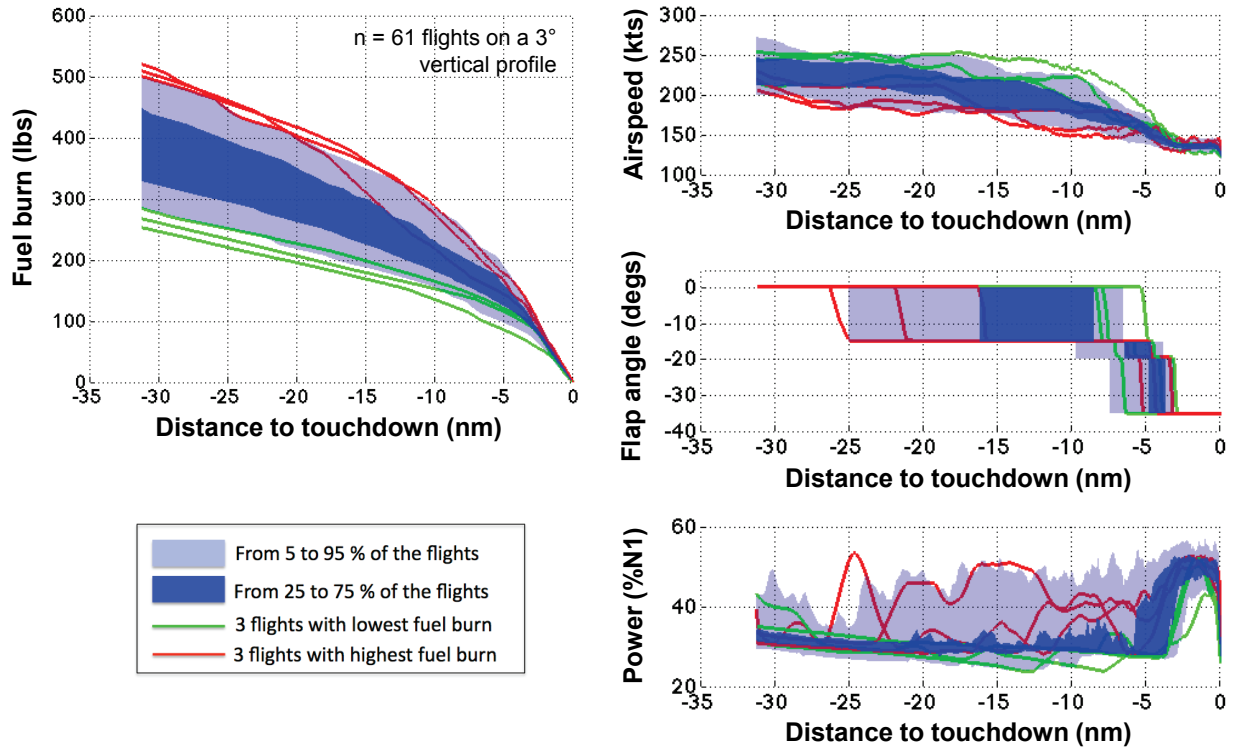


Figure 5: A320 Profile Results

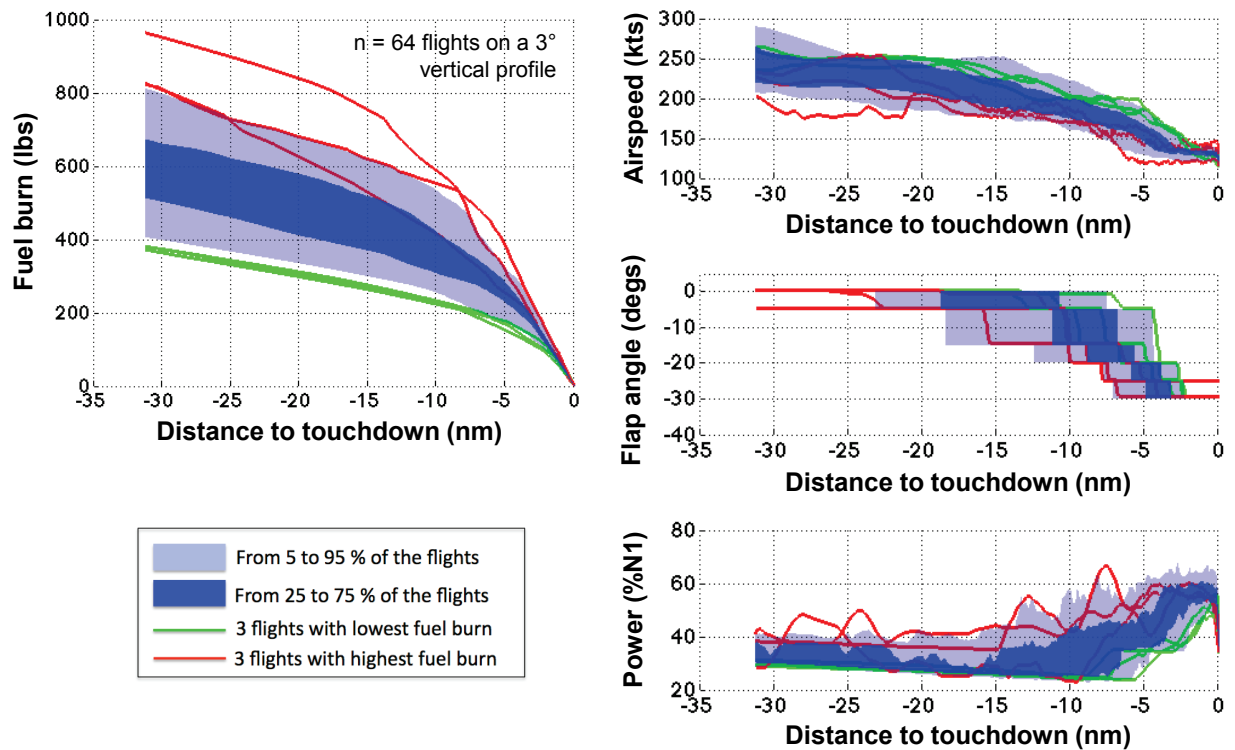


Figure 6: B757 Profile Results

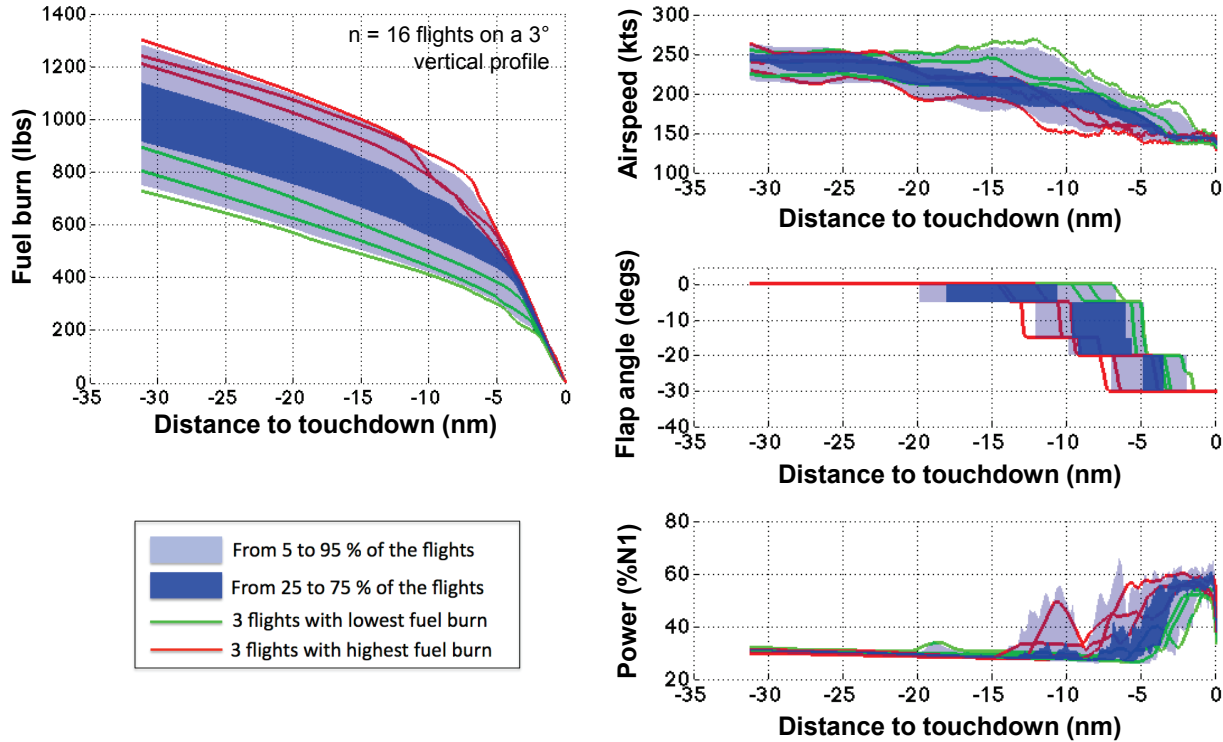


Figure 7: B777 Profile Results

Across the three aircraft types, some common themes are evident in the results. As expected, the larger aircraft tend to have larger fuel burns below 10,000 ft, but the lowest to highest fuel burn varies by approximately a factor of two for all three aircraft types studied. By comparison, the absolute ranges seen in the statistical summaries for the airspeed profiles are similar in the first part of the approach across the three aircraft types: the 5-95<sup>th</sup> percentile range is approximately 200-250 kts at 25 nm to touchdown, 175-250 kts at 15 nm to touchdown and 130-190 kts at 5 nm to touchdown. The statistical summaries for the flap angles show that the spread in the initial flap settings varies considerably across the three types, with early deployment (as far as 25 nm from touchdown) being most common in the A320, but then the larger flap angles tend to occur at 5-10 nm from touchdown for all types. Given the differences in available flap settings and aerodynamic characteristics between the aircraft types studied, such observed differences are to be expected. Finally, the engine power statistical summaries show the largest differences between types in the 5-95<sup>th</sup> percentile zone, with the A320 exhibiting the largest variation. By contrast, the 25-75<sup>th</sup> percentile zone was similar across the types, with a general trend of flight idle setting (approximately 30% N1) from 25-10 nm to touchdown, followed by engine spool-up (to 50-60% N1) for the final approach phase.

Further insights can be gained by examining the profiles of the flights with the three lowest and three highest fuel burns between the different flight parameters. From the figures, it is seen that the 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) and maintaining consistent flight idle engine settings until the final approach. The flights with the highest fuel burn exhibited the opposite characteristics: they decelerated and deployed flaps earlier in the approach and have significantly higher engine power than flight idle. A summary of the fuel burns of these flights relative to the average across all flights is presented in Table 1, together with carbon dioxide emission estimates and savings relative to block fuel burns for typical range/payload conditions<sup>§</sup>.

<sup>§</sup> Block fuel burns are estimated from PianoX [4]. A320-200: 500 nm range, 30000 lbs payload, 7070 lbs block fuel; B757-200: 1000 nm range, 39000 lbs payload, 16500 lbs block fuel; B777-200: 2000 nm range, 75000 lbs payload, 57000 lbs block fuel.

**Table 1: Approach Fuel Burn Summary**

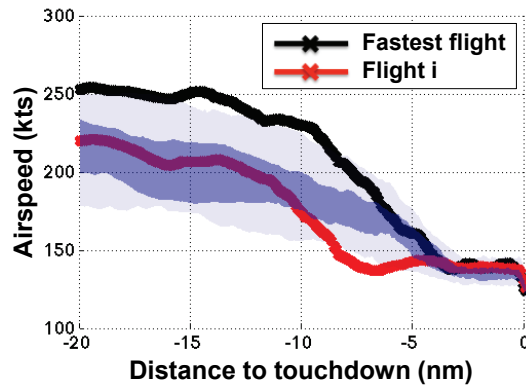
Aircraft Type	Approach Fuel Burn (10,000 ft to Touchdown)			Fuel Burn Difference Lowest to Average	Carbon Dioxide Difference Lowest to Average	Proportion of Typical Block Fuel Burn
	Average of Three Lowest Fuel Burn Flights	Average of All Flights	Average of Three Highest Fuel Burn Flights			
A320 (n=61)	268 lbs	383 lbs	509 lbs	115 lbs (30%)	165 kg	1.6%
B757 (n=64)	377 lbs	597 lbs	869 lbs	220 lbs (37%)	315 kg	1.3%
B777 (n=16)	726 lbs	1032 lbs	1298 lbs	306 lbs (30%)	438 kg	0.5%

The results suggest flights whose characteristics are consistent with LP/LD philosophy of delayed deceleration and flap deployment correspond to 30-40% fuel reductions below 10,000 ft compared to the average flight. However, more analysis was required 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, and these are explored next.

**C. Correlation Analysis**

This section analyzes the formal correlations between fuel burn and the LP/LD characteristics of late deceleration, flap and gear extensions to determine how much they individually contributed to the observed differences in fuel burn.

In order to characterize airspeed throughout the approach, the airspeed schedule of each flight was compared to the airspeed of the fastest flight, as illustrated in Figure 8. The average value of the speed difference was used as a metric to order flights by airspeed. A value of -20 kts, for instance, would mean that on average the considered flight was 20 kts slower than the fastest flight during the approach.



**Figure 8: Illustration of Airspeed Difference with Fastest Flight**

Figure 9 to Figure 11 show the fuel burn versus the average airspeed difference with the fastest flight, the distance for first extension of flaps (“Flap 1”), and the distance for gear extension for the three aircraft types (note the landing gear parameter was not available in the B777 FDR data). In each plot, red crosses represent individual flights, whereas the solid magenta line is a linear interpolation of the data points for all flights. The two dashed blue lines are the limits of the 95% prediction interval, which is the area in which 95% of the parameters are expected to be contained, considering the available data points. In addition, the square of the correlation coefficient for the linear interpolation is given at the bottom left corner of each graph.

The pronounced negative slope on the airspeed shows that high airspeeds (i.e. those with lower difference to fastest flight) correlate with low fuel burns. In addition, the first flap extension presents a similar negative slope, showing that later flap extensions also correlate with low fuel burn. Given the variability in the operational data, correlation coefficients of around 0.5 are considered significant in this analysis. On the other hand, gear extension is seen to be poorly correlated with fuel burn, with negligible slope and correlation coefficients lower than 0.2. In fact, the undercarriage is consistently extended at later stages of the approach (typically between 13 nm and 5 nm to touchdown), which decreases its effect on fuel burn differences between flights.

These results reinforce that the LP/LD characteristics of maintaining high airspeed during approach for as long as possible and delaying the first extension of the flaps are primary factors resulting in low fuel burn. However, the variability in the data indicates that other factors may have affected the fuel burn during approach. Therefore similar analyses on other external factors were also conducted: results for winds and differences in initial mass, altitude and speed (impacting total initial energy) conditions are presented next.

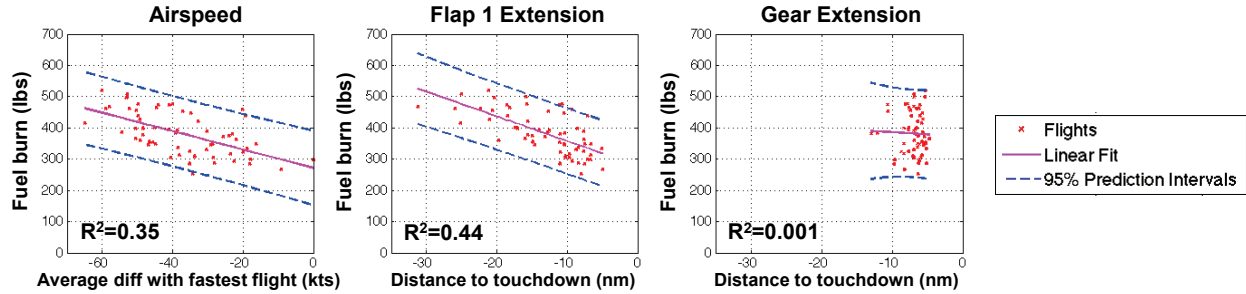


Figure 9: A320 Correlation Results

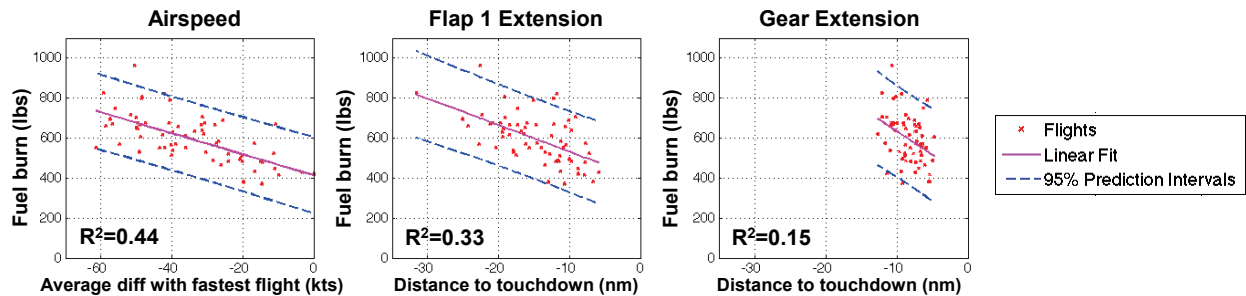


Figure 10: B757 Correlation Results

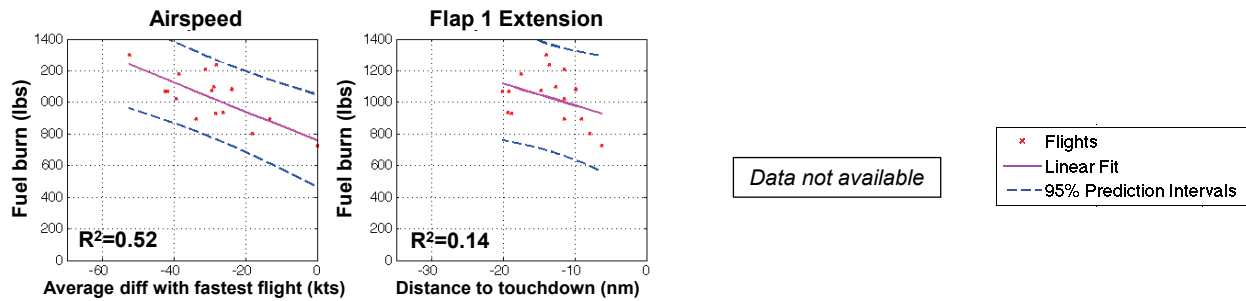


Figure 11: B777 Correlation Results

#### D. Wind Impacts

There was a significant amount of variability in the wind fields experienced by different flights in the FDR datasets given they were for flights across numerous days and geographic locations, and turns during the approach resulted in changing direction for the wind across the approach. In principle, consistent headwinds or tailwinds can impact fuel burn by affecting the air distance required to fly a given ground distance. The top plot of Figure 12 presents the fuel burns for all A320 flights in ascending order, and their corresponding average headwind during approach is in the bottom plot (negative headwind=tailwind). In addition, the solid blue line is a linear interpolation of the average headwinds (correlation factor of  $R^2=0.13$ ), and the blue shaded area indicates the 95% prediction interval based on this interpolation. It can be seen that there is indeed a relationship between headwinds and fuel burn, as higher headwinds led to higher fuel burns, although the slope is not very pronounced.

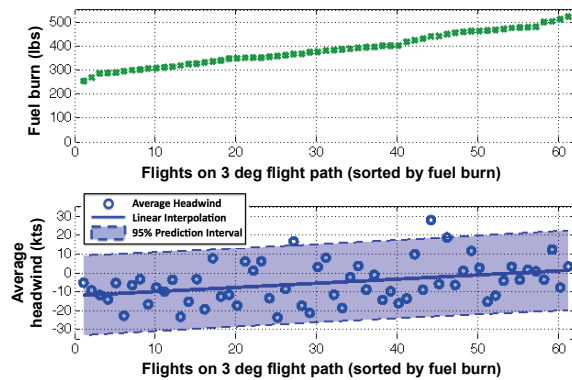


Figure 12: A320 Wind Field Impacts Analysis

The data also contains a lot of variability resulting in a low correlation factor. Even though there is a trend, this suggests wind is not the main factor responsible for the fuel burn differences. The same analysis was conducted for the other aircraft types and revealed even lower correlation coefficients ( $R^2=0.07$  for B757 and  $R^2=0.01$  for B777). It was therefore concluded that the differences observed in the results of Table 1 are not principally caused by differences in wind fields.

**E. Initial Energy Impacts**

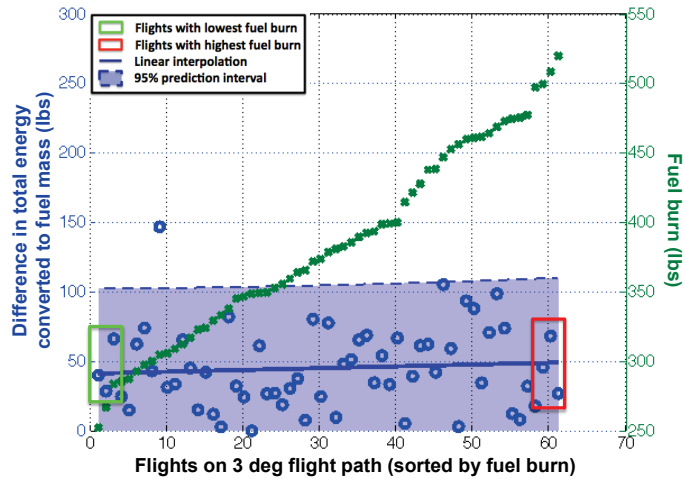
As previously highlighted, the scope of this study was restricted to the approach phase from 10,000 ft to touchdown. As observed in Figures 5-7, aircraft in the FDR data did not systematically have the same airspeeds at 10,000 ft, nor did they all have the same starting weights. This resulted in total energy differences between aircraft in terms of the sum of kinetic and potential energies, as defined by:

$$\Delta E_{Total}^{Approach} = E_{Total}^{10,000 ft} - E_{Total}^{Touchdown} = (E_{Kinetic}^{10,000 ft} + E_{Potential}^{10,000 ft}) - (E_{Kinetic}^{Touchdown} + E_{Potential}^{Touchdown})$$

Energy differences between flights may affect the fuel burn results. For example, flights with higher energy at 10,000 ft could have lower fuel burn compared to flights of the same aircraft type which enter with lower energy, as less fuel energy is then required to fly a given approach profile. Aircraft have higher total energy either because they remain in cruise for longer and therefore enter the terminal area with higher speed; or because they are heavier due to payload differences. In addition, the tolerances introduced in the altitude selection led to initial altitude differences of  $\pm 1,000$  ft (as shown in Figure 3). In order to analyze these effects, the impact of the differences in variation of total energy was estimated by considering how much fuel would be burnt at cruise to obtain the same amount of energy difference seen at 10,000 ft. This “equivalent fuel burn” quantity is defined as:

$$m_{Equivalent\ fuel\ burn} = \frac{\Delta E_{Total}^{Approach}}{LCV \cdot \eta_{Overall\ cruise}}$$

where  $LCV$  is the Lower Calorific Value of jet fuel (how much chemical energy is in the fuel = 43 MJ/kg, or 19.5 MJ/lb) and  $\eta$  is the overall cruise efficiency defining how much fuel energy is effectively converted into thrust. This efficiency was determined from Piano 5 [4] for representative missions to be between 30% and 35% for the three aircraft types studied. These equivalent fuel burns are plotted for the FDR analysis and sorted by fuel burn during approach in Figure 13. For the purpose of comparison, the reference of the equivalent fuel burn is taken to be the flight with the lowest value. Therefore, the number represented by the blue circles characterizes how much more energy a given flight possessed compared to the flight with lowest energy. The plot shows that there is no clear correlation between the fuel burn and the differences in total energy, despite significant variations in total energy. For instance, the three flights with lowest fuel burn (in the green rectangle at the left) have similar total energy on average than the flights with highest fuel burn (red rectangle at the right), suggesting that their difference in fuel burn was not caused by discrepancies in total energy. It is therefore concluded that the differences in initial energy between the flights are not the primary cause of the differences in observed fuel burn between flights.



**Figure 13: A320 Actual and Equivalent Fuel Burns**

In conclusion, these studies have shown that the primary factors leading to the observed differences in fuel burn were airspeed deceleration characteristics and location of flap extension, while effects of winds, location of gear extension and differences in initial energy have been identified as secondary factors.



## IV. US System-Wide Extrapolation and Barriers to Implementation

### A. US System-Wide Extrapolation

The results presented in the previous section demonstrate that flights with LP/LD characteristics hold significant promise for fuel burn reductions. They suggest that if an airline with a fleet of 100 Boeing 757s could conduct a single LP/LD approach by each aircraft per day (achieving 220 lbs fuel saving per flight as identified in Table 1), it would save 1.2 million US gallons of fuel (a cost saving of \$2.4-4.8 million at recent fuel price ranges of \$2-4/US gallon) and produce 11,500 metric tons lower carbon dioxide emissions per year\*\*.

In order to get a sense of the US system-wide potential impact of LP/LD approaches, a correlation of LP/LD fuel savings (consistent with the “lowest” relative to “average” results of Table 1) as a function of aircraft maximum gross take-off weight (MGTOW) was determined based on the FDR-based data points shown as diamonds in Figure 14. Representative MGTOW ranges were created to define “regional jet”, “small narrowbody”, “large narrowbody”, “two engine widebody” and “four engine widebody” aircraft classes. The regression line presented in Figure 14 was then used to estimate LP/LD fuel savings for aircraft in each aircraft class. Operational data was used to determine the proportion of flights of each class operating in the US. From this, an LP/LD “benefits pool” was calculated, representing an upper bound on possible fuel and emissions savings if all of the flights in the US were to conduct LP/LD approaches: see Table 2. The estimated fuel saving benefits pool is 5.3 million lbs per day or 290 million US gallons of fuel per year (with associated fuel cost savings of \$0.58-1.2 billion across all operators at \$2-4/US gallon price) and a carbon dioxide emissions reduction pool of 2.8 million metric tons per year.

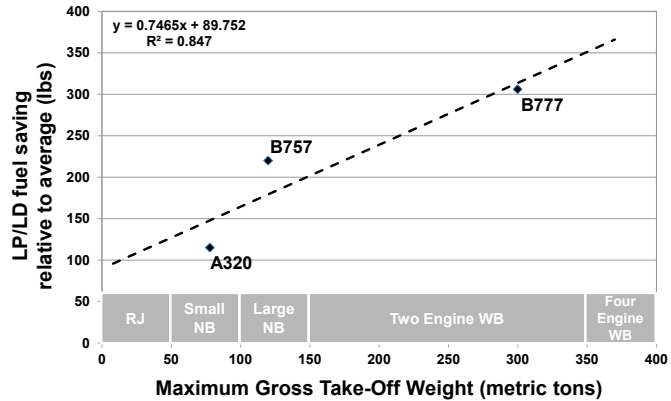


Figure 14: LP/LD Estimated Fuel Savings as a Function of Aircraft MGTOW

Table 2: US System-Wide LP/LD Benefits Pool Estimate

Aircraft Class	Example Aircraft Types	Representative MGTOW (metric tons)	Estimated LP/LD Saving Per Approach (lbs)	Approx. Number Flights Per Day	LP/LD Fuel Reduction Benefits Pool (lbs/day)	LP/LD Fuel Burn Reduction Benefits Pool (US gallons/year)	LP/LD CO <sub>2</sub> Reduction Benefits Pool (metric tons/year)
Regional Jet	CRJ ERJ	40	120	7,500	0.9 million	49 million	0.5 million
Small Narrowbody	A320 B737	75	146	14,400	2.1 million	115 million	1.1 million
Large Narrowbody	B757	125	183	1,800	0.3 million	18 million	0.2 million
Two Engine Widebody	A330 B777	250	276	3,900	1.1 million	59 million	0.6 million
Four Engine Widebody	A340 B747	375	375	2,400	0.9 million	49 million	0.5 million
<b>TOTALS</b>				<b>30,000</b>	<b>5.3 million</b>	<b>290 million</b>	<b>2.8 million</b>

\*\* Average LP/LD fuel saving for B757 = 220 lbs. Savings of one LP/LD approach per aircraft over 100 aircraft fleet = 22,000 lbs/day or 8.0 million lbs/year. Density of jet fuel ≈ 6.67 lbs/US gallon (where a US gallon ≈ 3.8 liters), so annual fuel savings equate to 8.0 million/6.67 = 1.2 million US gallons/year. Carbon dioxide emissions index = 3.16 lbs CO<sub>2</sub>/lbs fuel burnt, so 8.0 million lbs fuel/year = 25.3 million lbs CO<sub>2</sub>/year = 11,500 metric tons CO<sub>2</sub>/year.

In reality, not all flights can fly LP/LD approaches due to various implementation barriers. The proportion of approaches that are able to conduct LP/LD operations would determine the proportion of the benefits pool that is actually realized in terms of fuel savings. For example, if only 1% of the total system operations were to conduct LP/LD operations with fuel reductions suggested by Figure 14, the savings across all operators would amount to 2.9 million US gallons (\$5.8-11.6 million worth at \$2-4/US gallon) of fuel and 28,000 metric tons of carbon dioxide emissions per year. The implementation barriers which need to be overcome to enable LP/LD savings to become a reality are discussed in the next section.

## **B. Barriers to Implementation**

In the context of the spectrum of other operational mitigation opportunities explored in [1], the ease of implementation of LP/LD approaches was ranked as being of “medium” difficulty<sup>††</sup> because it requires some changes to existing approach procedures, taking into account aircraft safety and system capacity concerns, but does not need the establishment of any complicated infrastructure or rely on the introduction of new technologies. In addition, as long as LP/LD is implemented with existing vertical profiles, it is anticipated that no airspace changes would be required.

The fact that the FDR data is based on actual operations confirms that delayed deceleration approaches are possible in the current air traffic system under some conditions. However, the primary barriers to wider implementation of LP/LD today are air traffic control procedures, flight crew training and approach procedure design. As previously described, it is common in current-day operations for terminal area controllers to command early deceleration in order to get flights at a common speed and to increase the time available for spacing and sequencing traffic onto the final approach path to ensure maximum use of runway capacity. The later and less predictable deceleration across different aircraft associated with LP/LD approaches could increase controller workload at later stages of the approach. This could have potential consequences of controllers increasing the inter-aircraft separations during peak demand periods to reduce the aircraft arrival rate, with resulting loss of achieved runway throughput at these times. This would be an unacceptable consequence of implementing LP/LD procedures at many congested airports during peak periods. However, during periods of lower traffic, LP/LD approaches could be conducted without impacting controller workload. Traffic on a straight-in approach requiring little or no sequencing with other traffic presents the greatest current opportunity to conduct LP/LD approaches. Controllers sequencing aircraft from the downwind would need to factor in the greater turning radius of the aircraft to the final approach course resulting from the higher approach speeds. Considerations include, but are not limited to, the downwind distance from the final approach course (a wider downwind may be necessary in order to complete the turn), room to maneuver, sequencing aircraft from the downwind with aircraft already established on the final approach course and compression on the final approach. It is suggested that initial operating experience at lower demand periods at airports could enable considerable benefits to be realized while additional research is conducted into mitigating impacts of LP/LD on controller workload and throughput. In addition, wider use of LP/LD approaches at non-capacity constrained airports may be possible from an air traffic control perspective at this time given sufficient prioritization and should be explored in greater detail in future work.

In addition to the air traffic controller consequences, potential impacts to flight crew of the later deceleration and flap deployment needs to be carefully considered. The final approach phase of flight is typically relatively high workload, and hence human factors implications of LP/LD on the flight deck needs to be explored to make sure any adverse consequences are identified and mitigated. Airline participation in this process, together with discussions on flight crew training protocols which may be relevant to wider LP/LD implementation, are strongly recommended for future work.

The wider development and deployment of Area Navigation (RNAV) approach procedures also has implications for delivery of benefits from LP/LD. These types of approach procedures are programmed into the aircraft FMS in terms of waypoints, with altitude and speed targets at some of the points. Whenever speed targets are used, they can cause early deceleration and flap deployment just the same as tactical air traffic controller speed commands. Unless

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<sup>††</sup> In [1], “medium” difficulty of implementation was defined as mitigations requiring relatively uncomplicated technology or infrastructure additions (e.g. adding more (but existing) technology or building “simple” infrastructure such as a new taxiway), relatively minor modifications to procedures and/or straightforward policy review, but no airspace changes.

there are other operational reasons for requiring early deceleration, RNAV approach procedures with speed targets which are sensitive to LP/LD objectives provide a tremendous opportunity to achieve benefits from the approach while mitigating some of the air traffic control and flight crew concerns identified above. For example, if the FMS is managing the speed profile during the final stages of the approach, some of the flight crew workload implications might be reduced. This does require careful analysis of appropriate speed targets during RNAV procedure design to achieve LP/LD objectives at the same time as many other factors, but recent advanced approach procedure development activities have proved this to be possible [3,5].

## V. Conclusions

Low Power/Low Drag approaches which delay the deceleration to keep aircraft fast and in clean configuration for as long as possible during approach operations have been the focus of this paper. Using Flight Data Recorder from three representative aircraft types restricted to continuous three degree glide path approaches, it has been shown that lowest fuel burns were achieved when aircraft kept their airspeed high and delayed their flap extension for as long as possible during the approach while still complying with current final approach stabilization criteria. Conversely, the highest fuel burns during approach occurred simultaneously with early deceleration and flap extension. A correlation analysis confirmed that delay of airspeed deceleration and flap extension were the primary factors leading to the differences in fuel burn, and these are consistent with the philosophy of delayed deceleration LP/LD approaches. Although contributing to the variability in the data, it has been shown that winds and differences in initial approach energy were not principal contributors to the observed differences in fuel burn.

This study suggests that savings of 30-40% of fuel burn below 10,000 ft can be enabled with the implementation of LP/LD approaches. Note that, had the three degree flight path constraint in this analysis been released, savings from LP/LD could be even higher. A system-wide extrapolation to the US network estimated a fuel reduction benefits pool of 290 million US gallons of fuel and 2.8 million metric tons of carbon dioxide emissions reduction per year could be obtained if all flights were to fly LP/LD approaches. However, implementation barriers such as air traffic controller, pilot workload or specific airport procedures must be addressed to enable wider utilization of LP/LD approaches and therefore enable the maximum fraction of this benefits pool to be realized. But if even 1% of US flights could operate LP/LD approaches, savings across all operators would amount to 2.9 million US gallons (\$5.8-11.6 million at \$2-4/US gallon) of fuel and 28,000 metric tons of carbon dioxide emissions per year.

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