Fuel Burn Reduction Potential from Delayed Deceleration Approaches

by

Jean-Marie Dumont

Submitted to the Department of Aeronautics and Astronautics
in Partial Fulfillment of the Requirements for the Degree of

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Author . . . .
Department of Aeronautics and Astronautics
August 14, 2012

Certified by . . . .
R. John Hansman, Jr.
Professor of Aeronautics and Astronautics
Thesis Supervisor

Certified by . . . .
Tom G. Reynolds
Technical Staff, MIT Lincoln Laboratory
Thesis Supervisor

Accepted by . . . .
Eytan H. Modiano
Professor of Aeronautics and Astronautics
Chair, Graduate Program Committee

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Abstract

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. One promising modification comes from increasing the use of Delayed Deceleration Approaches where the deceleration to the standard stabilized final approach speed occurs later, which keeps the aircraft in clean aerodynamic configuration with low thrust for as long as possible. Although such approaches can reduce fuel burn, in practice aircraft often decelerate much earlier. This may be for a variety of reasons, such as airspace restrictions, slower traffic ahead, air traffic controller technique and airline procedures and/or pilot technique.

In this study, operational flight data has first been used to quantify the potential fuel burn savings associated with Delayed Deceleration Approaches. 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 Delayed Deceleration Approaches have also been produced.

Second, radar tracks of flights to different airport areas have been analyzed to help identify reasons for early decelerations. By observing the context of evolution of the less fuel efficient flights, the role of different potential factors such as preceding traffic, traffic mix, highly constrained airspace, runway interactions and severe weather conditions affecting the airspeed schedule of a given flight have been examined. Weather appeared to be a major parameter affecting the airspeed schedule, and air traffic procedures involving early decelerations appeared to have been used in dense and complex airspaces.

Thesis Supervisor: R. John Hansman
Title: Professor of Aeronautics and Astronautics

Thesis Supervisor: Tom G. Reynolds
Title: Technical Staff, MIT Lincoln Laboratory

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Disclaimer

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Nomenclature

ASPM	Aviation System Performance Metrics
ATC	Air Traffic Control
CAS	Calibrated Airspeed
CDA	Continuous Descent Approach
DDA	Delayed Deceleration Approach
DFDR	Digital Flight Data Recorder
FAA	Federal Aviation Administration
IMC	Instrumental Meteorological Conditions
LP/LD	Low Power/Low Drag
MGTOW	Maximum Gross Take-Off Weight
NCDC	National Climatic Data Center
PDARS	Performance Data Analysis and Reporting System
SOP	Standard Operating Procedures
TAS	True Airspeed
TRACON	Terminal Radar Approach Control
VMC	Visual Meteorological Conditions

Chapter 1

Introduction and Motivation

1.1 Background

Aviation has been receiving increasing attention with respect to its contribution to global warming and other environmental effects. Simultaneously, the rising cost of fuel — the most important single expense for airlines — catalyzes motivations for increasing fuel efficiency. Amongst the various strategies to reduce fuel burn and mitigate the environmental impacts from aviation, those with the highest potential such as developing advanced aircraft will take a long time to have major benefits. This motivates the assessment of benefits from modifying operational procedures, which have smaller overall mitigation potential compared to the other options, but can be implemented in much shorter timeframes with existing aircraft types [1, 2]. An example of the motivation to improve fuel efficiency through operations is the assessment of the 3-Dimensional Inefficiency Score (3Di Score) in the UK air traffic control (NATS), which penalizes track extension or vertical inefficiencies and help controllers route aircraft as close to the environmental optimum as possible [3].

Fuel reduction can be achieved through operational changes at different stages of the flight: during taxiing, for instance by using gate holding to reduce taxi time [4]; during take-off and climb, by using as little flap as necessary and retracting gear and flaps early [5]; during cruise, by flying at fuel optimum altitude and airspeed [6]; or during descent, which has been the focus of many recent studies. For instance, Davidson and Hunter, as well as Knorr et al. have identified the time and fuel burn benefit pool during descent from increasing vertical and horizontal efficiencies, respectively by suppressing low altitude level flight segments and by flying the shortest arrival trajectory (suppressing holdings or extended downwinds)[7, 8]. In particular, the optimization of the vertical trajectory with the so-called Continuous Descent Approach (CDA) or Optimum Profile Descent (OPD), has been covered by comprehensive studies on operational limitations and wind effects, along with real scale flight test trials [9, 10, 12, 13, 15]. These provide not only fuel burn and emission benefits, but also help reduce the noise over local communities around the airport by removing the low altitude/high thrust level flight segments.

However, little work has been done on optimizing the speed profile during approach to maximize fuel burn, either independently or in conjunction with the optimum vertical profile. Amongst the few studies on that matter, a Boeing article directed to operators identified the fuel burn reduction potential from delaying the flap extension [14] and a paper for the Air Traffic Management Research and Development Seminar 2007 motivated Low Speed and Low Power/Low Drag approaches to reduce aircraft generated noise [15]. Nevertheless, extensive studies quantifying the fuel burn benefits from optimum speed management in approach and the degree to which these benefits can be achieved in real operations are missing.

1.2 Delayed Deceleration Approaches

As aircraft slow down during approach, they eventually need to extend their slats and flaps to enable higher lift for low airspeeds, but this also increases the drag of the aircraft. As a consequence, thrust, and hence fuel flow, have to be increased to match the added drag. Additionally, the extension of the undercarriage as the plane prepares for landing also increases thrust and fuel flow required due to drag increase. If the deceleration is executed far away from the airport, then an extended period of time is spent with high fuel flow; this will result in a higher fuel burn approach than if the deceleration was delayed.

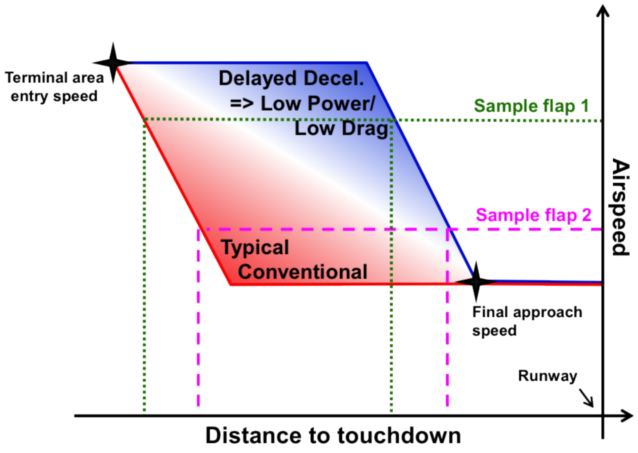


Figure 1-1: Comparison of Delayed Deceleration and Conventional Airspeed Profiles

Figure 1-1 presents a conceptual comparison of aircraft speed profiles as a function of distance to touchdown for a Delayed Deceleration Approach (DDA) versus conventional deceleration approaches where speed is reduced earlier. 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 10,000 ft) and the final approach stabilization speed.

Flight crews and TRACON controllers have some flexibility in selecting the speed profile between these two constraints. In typical conventional approach operations, aircraft often decelerate relatively early in their approach trajectory, resulting in higher approach fuel burn and emissions. This can be for a number of reasons, for example crews may configure early in challenging weather conditions or air traffic control may command early deceleration to give more time to space and sequence traffic flows onto the final approach. On the other hand, Delayed Deceleration Approaches maintain a higher speed 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. Note that 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 DDA profile (where deceleration to final approach speed occurs at the last possible moment), as shown in Figure 1-1.

It is also important to note that the DDA philosophy is complementary to the widely-studied CDA procedure in that the DDA focus is on the approach speed profile while the CDA primary focus is on the approach vertical profile. The fuel optimum case is thus to fly a Delayed Deceleration Approach speed profile while on a Continuous Descent Approach vertical profile.

Although such approaches can reduce fuel burn, in practice aircraft in the operational system are often observed to decelerate much earlier. This may be for a variety of reasons, such as air traffic controller technique, airspace restrictions, interactions with other traffic (e.g. slower traffic ahead), airline procedures and/or pilot technique. Therefore, there is a need to better understand the potential benefits of DDA procedures and barriers to their implementation so increased usage can be motivated in cases where it makes sense to do so.

1.3 Research Objective

The aim of this research is to provide an assessment of the fuel burn reduction potential from Delayed Deceleration Approaches in the context of air traffic operations. Specifically, this thesis' objectives are to:

- Quantify the potential fuel burn savings from DDA procedures
- Assess the barriers to implementation from current context of operations and propose mitigations to increase the usage of DDAs.

The findings of this work could be useful for airlines to improve their fuel efficiency; for the design of new approaches, in particular with the introduction of NextGen capabilities; and for air traffic controllers through the identification of benefits and limitations of DDAs in terms of key performance measures such as flight efficiency and airspace/airport throughput.

1.4 Research Approach and Thesis Outline

First, an aircraft level analysis with DFDR archive data from flight operations was performed to quantify the fuel burn and emission reduction potential of DDAs and is reported in Chapter 2. This analysis has also tested several parameters for correlation with fuel burn, in order to identify how much of the observed variations in fuel burn were affected by external factors (such as wind or differences between initial conditions of the study). First order estimates of system wide benefits from operating DDAs were calculated based on these results.

Second, potential barriers of implementation for DDAs have been analyzed as reported in Chapter 3. Two approaches were used: i) discussions with airlines and air traffic controllers were conducted to help identify the possible limitations of DDA; and ii) a system level analysis using radar data was performed to observe flights in their context of evolution. Potential correlations between fuel efficiency and factors such as close preceding traffic, high traffic mix, highly constrained airspace, runway interactions or severe weather conditions have been studied. Mitigations for some of the limitations identified were also suggested so as to extend the use of DDAs in the current context of operations.

Conclusions from this work and recommendations for future work are presented in Chapter 4.

Chapter 2

Aircraft Level Analysis

This chapter evaluates potential fuel burn savings for individual aircraft from delaying the deceleration during approach. Operational Digital Flight Data Recorder (DFDR) data have been used as they give high visibility into the performance of flights.

2.1 Methodology to Assess Effects of Speed Management on Fuel Burn

2.1.1 Overview

The approach used to assess the fuel burn reduction potential at the aircraft level was based on airline operational data. The study has been limited to the phase of approach that is between 10,000 ft over the destination airport elevation and touch down. Various parameters that characterize Delayed Deceleration Approaches — such as airspeed and extension of flaps — are observed and correlated to fuel burn performance to find potential relationships. A formal statistical analysis was also conducted to sort all factors that contributed to the observed variations in fuel burn by order of importance; this latter analysis also included external factors such as wind and variations of payload weight within an aircraft type to check for their potential contributions in fuel burn variation between flights.

The methodology used in this section is illustrated in Figure 2-1 and is detailed in the following subsections.

2.1.2 DFDR Data

2.1.2.1 Parameters

The following analyses were based on an available DFDR archive, which comprised detailed data of a flight's evolution. The primary purpose of these data is to provide information in the case of an incident or accident

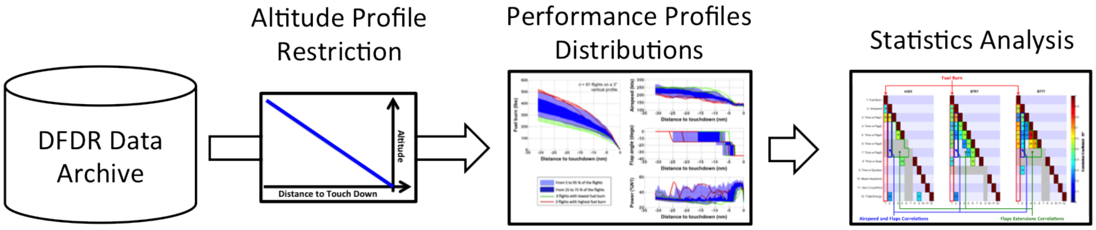


Figure 2-1: Aircraft Level Analysis Methodology

involving the aircraft; additionally, these data are used for quality assurance within the airlines. Most aircraft record about 100 parameters for the full duration of a flight, not only including position and altitude but also fuel flow, position of thrust lever, extension of flaps, etc. The sample rate at which these data are recorded varies with the phase of flight; for the approach, 1 second and 10 second intervals are used respectively below and above 5,000 ft.

The DFDR data used for this study contained operations during 2005 from a European-based airline. No US based operations data were available.

Figure 2-2 shows some sample plots extracted from these data for a single flight, where all four parameters have been plotted as a function of distance to touch down.

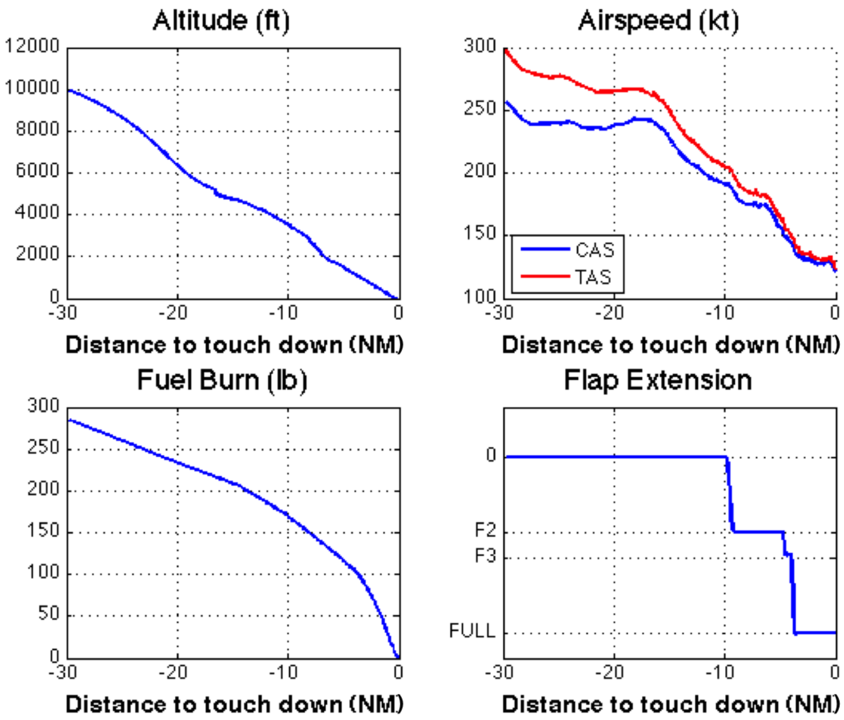


Figure 2-2: Example of Data from Digital Flight Data Recorder

Altitude This specific flight follows a continuous descent approach on a 3 degree descent profile, as represented on the top less plot.

Airspeed The airspeed (top right) is reported in true airspeed (TAS) and calibrated airspeed (CAS). True Airspeed is the speed of the airplane relative to the airmass. However, pilots use Calibrated Airspeed instead, which is obtained from a Pitot probe. This latter directly describes the dynamic pressure acting on the airplane so that it can be compared to reference airspeeds such as stall speed or maximum airspeed, independently of density altitude, winds, etc. The main difference between the two airspeed comes from density. In particular, TAS is equal to CAS at sea level, whereas TAS will be higher than CAS as altitude increases (and density decreases). This means that a descent at constant CAS includes in fact a deceleration with respect to TAS, as illustrated in Figure 2-2. However, this study will refer to the Calibrated Airspeed whenever mentioning decelerations or constant airspeed, since this is the information that pilots use.

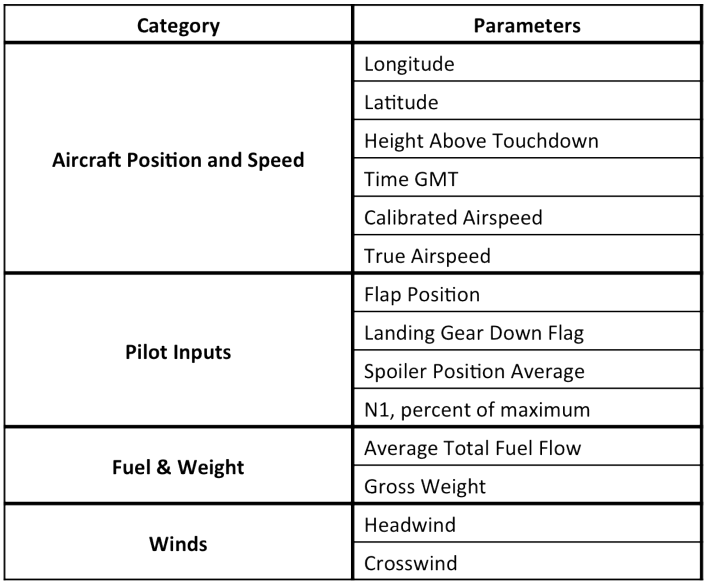
Fuel Burn The fuel burn plot (bottom left) is a backwards integration of the fuel flow, starting from touch down; as such, it represents the fuel burn that has been burnt between a given point and touch down. For example, the first value (30 nm away from touch down) represents the total fuel burn between 10,000 ft and touch down for this flight.

The fuel burn curve exhibits a marked change in slope at around 4 nm before touch down. This most likely indicates that the aircraft is being set into its final landing configuration and requires additional thrust (and hence fuel burn) to match the increase of drag generated by the extension of flaps and gear.

Flap Extension The bottom right part of the plot shows the amount of flaps extension. This aircraft presents three positions for flap extensions: 15, 20 and 35 degrees. These correspond to the last three positions of the flaps lever, F2, F3 and FULL, as the first position only extends slats. The extension of flaps coincides with the deceleration of the aircraft. If fact, to a very good approximation, the flap extension schedule is a function of the airspeed, as the range of airspeed that can be flown for each extension degree is fairly limited. The final extension of flaps happened at around 4 nm to touch down, which coincides with the increase in the slope of fuel burn previously noticed.

Although information on the extension of the slats would be valuable, it was not available from the DFDR data and slat extension will not be further discussed in this work.

Other Parameters Other parameters available from the DFDR data include the landing gear position, spoilers position, rotation speed of the engine fan (called N1 as the fan is the first spool of the engine) as listed in Table 2.1.



Category	Parameters
Aircraft Position and Speed	Longitude
	Latitude
	Height Above Touchdown
	Time GMT
	Calibrated Airspeed
	True Airspeed
Pilot Inputs	Flap Position
	Landing Gear Down Flag
	Spoiler Position Average
	N1, percent of maximum
Fuel & Weight	Average Total Fuel Flow
	Gross Weight
Winds	Headwind
	Crosswind

Table 2.1: DFDR Parameters Used in this Study

2.1.2.2 Aircraft Selection

Three different aircraft types have been selected for these analyses: an Airbus A320, a Boeing 757 and a Boeing 777. These aircraft are respectively a small narrow-body, a bigger narrow-body and a wide-body with typical seating capacities and Maximum Take-Off Weights (MTOW) as shown in Table 2.2.

	A320	B757	B777
Seating Capacity (2-class, typical)	150	200	400
Maximum Take-Off Weight (MTOW)	129,000 lb	255,000 lb	545,000 lb

Table 2.2: Comparison of Aircraft Selected for Study

These three example should provide some insights about the effect of the aircraft size on the potential for fuel burn savings from DDAs.

2.1.3 Altitude Profile Restriction

Analysis was limited to flights on approximately 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 2-3. The tolerances for upper and lower boundaries around the three degree profile were ±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 (the DFDR data was from European operations), but it also meant the analysis was conducted on flights following CDA vertical profiles. Therefore, the key differences between the flights analyzed was in their speed and flap configuration profiles, allowing the main impacts of interest to a DDA assessment to be isolated. The three degree slope was chosen since it was the most common altitude profile from the DFDR data.

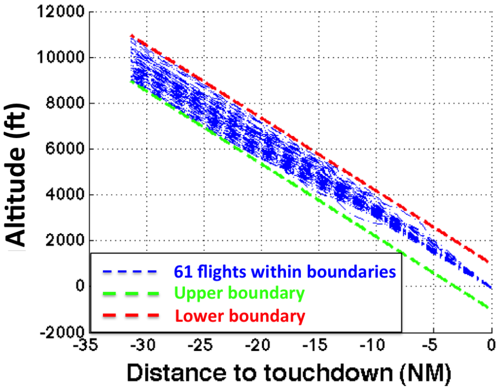


Figure 2-3: Definition of Three Degree Approach Path

	A320	B757	B777
Number of Flights	61	64	16

Table 2.3: Number of Flights on a Three Degree Descent Profile from the DFDR Data

The total number of flights available for each aircraft type after this filtering is shown in Table 2.3. These numbers are high enough to perform statistical analysis, although there is less confidence associated with the B777 due to lower number of flights available.

2.1.4 Performance Profile Distributions

The main parameters of interest to evaluate the potential for fuel burn reduction from DDA were: fuel burn, airspeed, flap extension, landing gear position and engine power level (altitude was not included since all flights for the analyses had similar altitude profiles). All parameters have been studied as a function of distance to touch down, starting from 31.4 nm where the three degree descent profile intersects the 10,000 ft altitude.

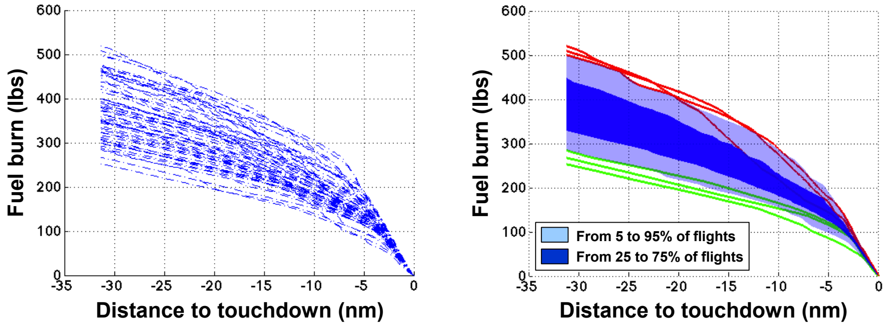


Figure 2-4: Sample A320 Fuel Burn Profiles (left) and Statistical Summary (right)

In order to provide an easy visual representation of how flights performed along their various parameters, color patches representing the distribution of all flights have been used, inspired from the work of Li et al.

[20]. An example of this visualization approach is given on Figure 2-4 with the 61 fuel burn realizations of the A320 flights from the DFDR data. The left plot represents each of the flights, whereas the right plot presents the data in terms of 5^{th}, 25^{th}, 75^{th} and 95^{th} percentiles. These statistical parameters provide important insights on 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 width of the blue patches is therefore indicative of how spread the data is; for instance, narrow blue patches would indicate that most flights have very similar behavior.

In addition, the three flights with lowest and highest fuel burns have been plotted in green and red respectively.

This representation provides an easy visual assessment of the average behavior (dark blue patch) and of the variation in the data (lighter blue patch and three most and least efficient flights in green and red respectively). Therefore, it is possible to apply this representation to several parameters of interest and simultaneously visualize their evolution. Performance profiles showing fuel burn, airspeed, flap extension and power setting have been generated to analyze the effects of DDA in the following of this study (see 2.2).

2.1.5 Statistical Analysis

2.1.5.1 Objective

The distribution representation of performance profiles should provide a visual understanding of the effects of the speed management on fuel burn. However, other parameters not represented in these plots may have affected the distribution of the fuel burn, such as winds or differences in potential or kinetic energies of the aircraft for instance. Therefore, a more formal analysis of how much airspeed could be held responsible for the variations in fuel burn has been conducted. More generally, this statistical analysis aimed at identifying the relationship between fuel burn and all other factors that may have played a role in order to separate the parameters between primary factors and less important secondary factors mainly introducing noise in the data. This was done by calculating the correlation coefficients between fuel burn and other relevant parameters.

2.1.5.2 Metrics used

The parameters involved in the correlation analysis with fuel burn were the following:

- Airspeed
- Flaps, gear and spoiler extensions
- Winds
- Total Energy

In order to suit the correlation with the total fuel burn during approach (defined as 10,000 ft to touch down), these metrics had first to be manipulated into a single value for each flight.

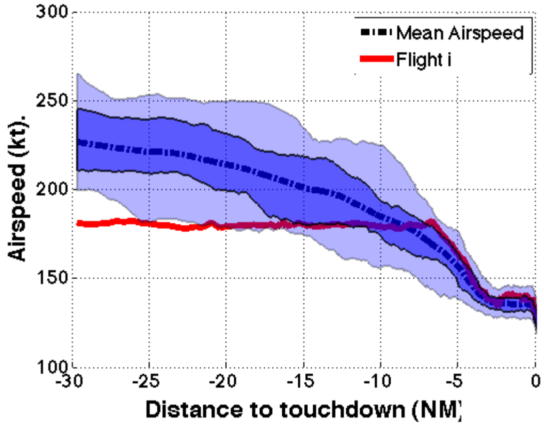


Figure 2-5: Illustration of Airspeed Difference with Fastest Flight

Airspeed In order to characterize airspeed throughout the approach, the airspeed schedule of each flight was compared to the average airspeed of the distribution (from all flights on a three degree slope), as illustrated in Figure 2-5. The average value of the speed difference with the mean was used as a metric to order flights by airspeed; for instance, the flight presented in Figure 2-5 is on average 19 kts slower than the mean of the distribution during approach. This metric characterizes how fast a given flight flew its approach from 10,000 ft to touchdown.

Flaps, gear and spoiler extensions Flaps, gear and spoilers indirectly affect fuel burn by increasing the drag of the aircraft; their extension often leads to an increase in thrust, and hence results in a higher fuel flow. Because fuel burn is the integration of fuel flow over time, a relevant metric to quantify their correlation with fuel burn is to calculate the time they have been extended before touch down.

(degrees)	A320	B757	B777
FLAPS	15 20 35	5 15 20 25 30	5 15 20 30

Table 2.4: Degrees of Flap Extension by Aircraft Type

For the flaps, the time of extension has been broken down for each possible degree of extension for the flaps (e.g. time with flap 1 extended, etc.), as detailed on Table 2.4. An illustration of the time flown with flaps extended for a sample A320 flight is provided in Figure 2-6.

For the spoilers, the amount of their extension has been integrated over time. Hence, the value of this metric represents the cumulative spoiler extension over the descent in $minute \cdot degree\, of\, extension$. For

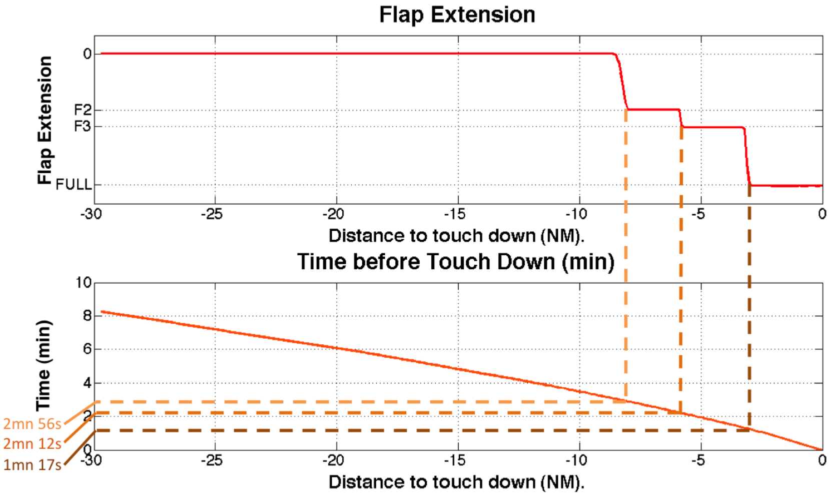


Figure 2-6: Illustration of Time Flown with Flaps Extended

example, fully extending the spoilers during one minute with an A320 would results into 25 $min \cdot deg$, since the position of full extension corresponds to 25 deg. If two minutes are flown with that amount of spoilers, then the metric becomes 50 $min \cdot deg$. Figure 2-7 shows an example for an A320; the corresponding value of the metric is 19.7 $min \cdot deg$ (about 40 seconds spent with 16 deg and 20 seconds with 25 deg).

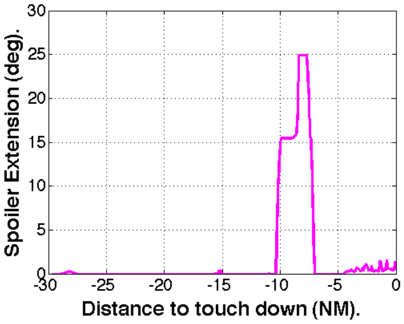


Figure 2-7: Illustration of Spoiler Extension

Wind Winds have output as headwinds and crosswinds from the DFDR data. Similarly to the airspeed, they have been compared to the zero wind case to account for how much wind affected the flight during approach. Headwinds were counted positively whereas tailwinds were counted negatively; crosswinds were counted positively both ways, such that positive values always represent a resistance to the flight. Figure 2-8 presents an example of winds and shows the corresponding value of the wind metrics in magenta.

Variation of Total Energy In order to account for differences in the initial energy that may have influenced fuel burn, the variation of total energy — sum of potential and kinetic energies — between the start of the study and landing were calculated. The main factors responsible for differences in energy between flights

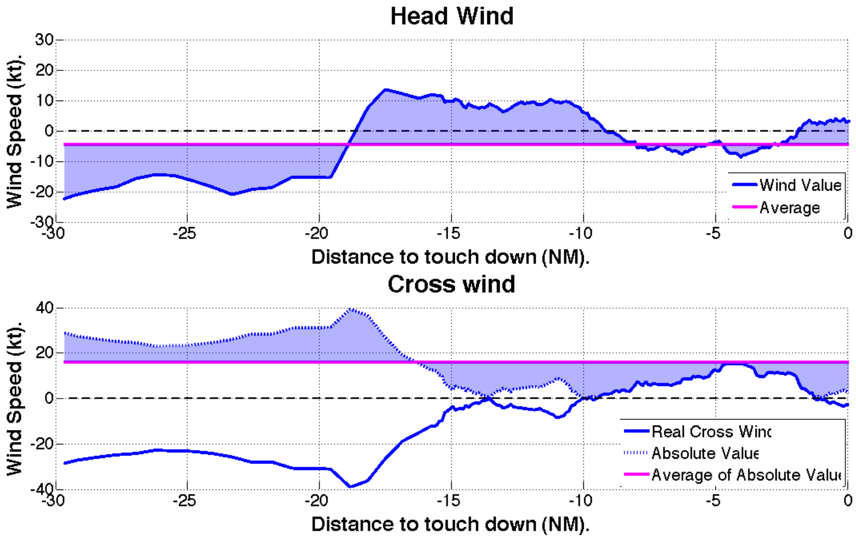


Figure 2-8: Illustration of Average Wind

at the beginning of this study are the mass, varying within a given aircraft type due to different payloads; the initial airspeed (when crossing the 31.4 nm cut-off for the scope of this study); and the initial altitude, due to the tolerances around the three degree descent profile introducing ±1,000 ft variations. Equation 2.1 shows how the difference in total energy between the start and end of the study was calculated[1]. This difference of energy was recovered by the aircraft during descent, such that heavier, faster or higher aircraft may have been favored during approach compared to lighter, slower or lower aircraft (of course, the former were penalized more during climb and acceleration as well, but this is not part of the analysis conducted here).

$$\Delta E_{tot} = \triangle E_{pot} + \Delta E_{kin} = m_{ini} \cdot g \cdot h_{ini} + \frac{1}{2} \cdot m_{ini} \cdot V_{ini}^2 - \frac{1}{2} \cdot m_{fin} \cdot V_{fin}^2 \simeq m \cdot (g \cdot h_{ini} + \frac{V_{ini}^2 - V_{fin}^2}{2}) \quad (2.1)$$

The magnitude of the variations in difference of total energy during descent is represented in Figure 2-9. Within a given aircraft type, each flight is represented by a magenta cross, and boxplots represent the 25^{th} and 75^{th} percentiles of the distribution[2]. As expected, the magnitude of the total energy increases with aircraft type due to increasing weight. However, these plots also show that for each aircraft types, there is a significant variation in the amount of energy that can be recovered during descent.

Therefore, the statistical study has also looked for potential correlations of fuel burn with total energy in order to assess how much these variations affected the results on fuel burn.

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[1] The final altitude is by definition 0 since altitude is defined here as elevation above destination airport.

[2] Outliers are points that would be outside the range $[-2.7\,\sigma, 2.7\,\sigma]$, which would represent 99.3 % coverage if the data were normally distributed

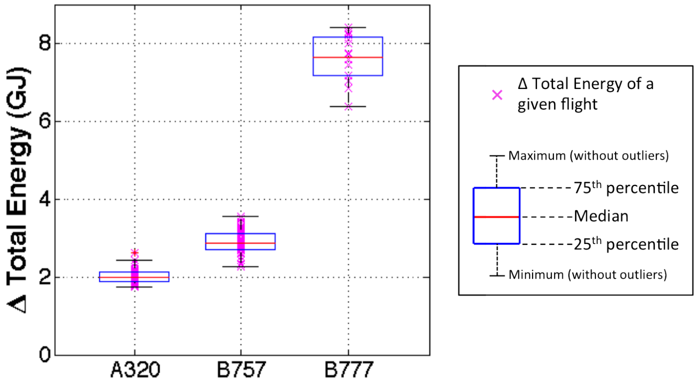


Figure 2-9: Variability in Difference in Total Energy Across Approach

2.2 Performance Profiles

2.2.1 Distributions of Fuel Burn

Figure 2-10 presents the fuel burns of the three aircraft types according to the methodology presented in Section 2.1.4. The expected increase in magnitude of fuel burn with aircraft size is visible, but the shape of the distributions are very similar. The spread in fuel burn is the highest at 31.4 nm from touchdown, at which point the 95^{th} percentile is almost twice the value of the 5^{th} (extremes of light blue patch), i.e. fuel burn difference is about twice between highest and lowest fuel burn flights. In addition, the average slope of the distribution is approximatively constant between 30 nm and 10 nm, and only becomes steeper for the last 5 nautical miles where thrust levels and hence fuel flows are higher. For the last 3 nautical miles, all flights within a given aircraft type present the exact same slope of fuel burn, as indicated by the very tight distributions. This is consistent with the fact that at that point, aircraft are all set to their reference airspeed and in their landing configuration, such that their thrust and hence fuel flows are very similar.

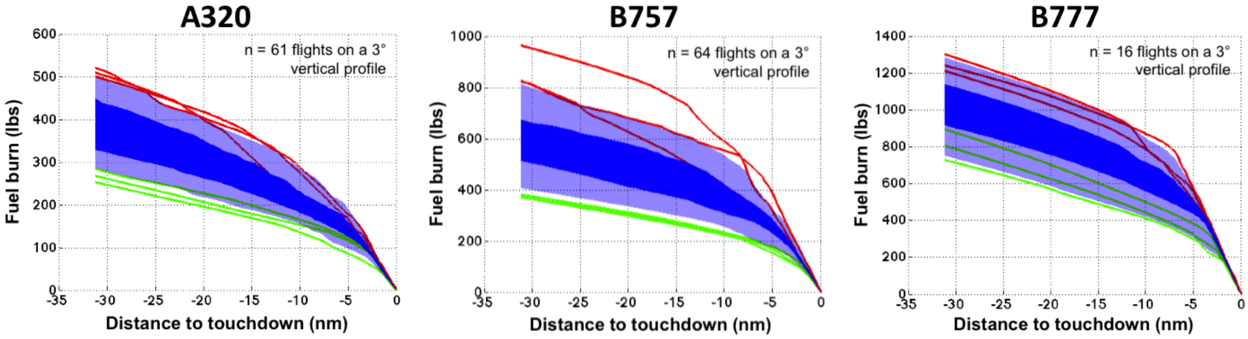


Figure 2-10: Fuel Burn Distributions for the Three Aircraft Types

It is interesting to note that for the B777, the fuel burn plots are fairly parallel between 30 and 10 nm.

This shows that the overall spread of fuel burnt during the approach is mainly caused by differences between 3 and 10 nm to touch down; in particular, the least efficient flights spent the last 5 to 6 nm with a steep fuel burn portion (high fuel flow) whereas the most efficient only remained 3 nm in that phase. This suggest that the variations in fuel burn are influenced by the time at which the aircraft are set to landing configuration.

2.2.2 Observed Variations in Speed Management

More insights are gained about the relationship between fuel burn and speed management by observing the airspeed, flaps and power setting at the same time. Figure 2-11, 2-12 and 2-13 present this set of parameters for the three aircraft types of the study. 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.

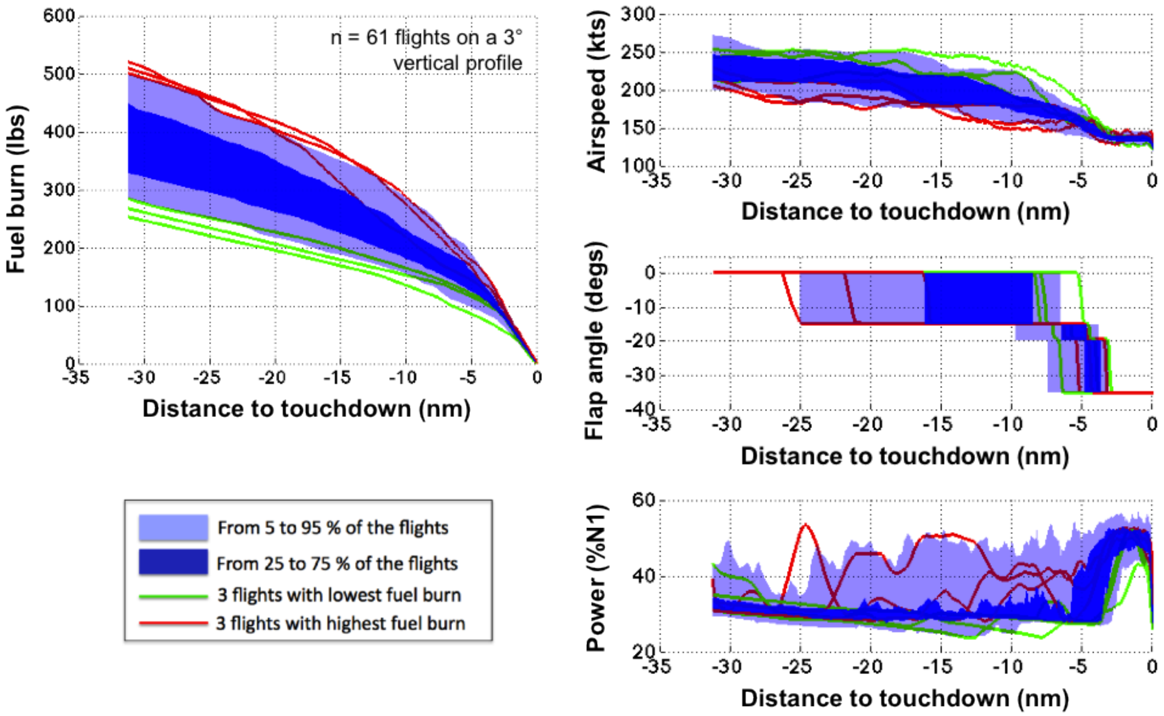


Figure 2-11: A320 Profile Results

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 5-95th 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

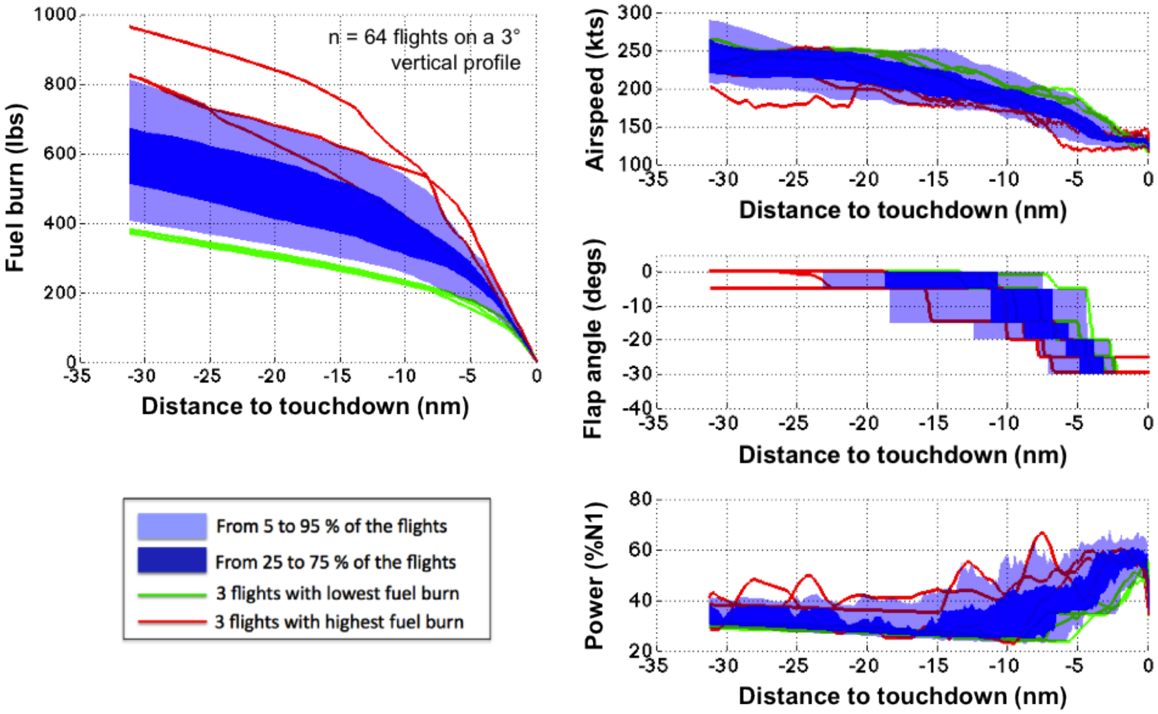


Figure 2-12: B757 Profile Results

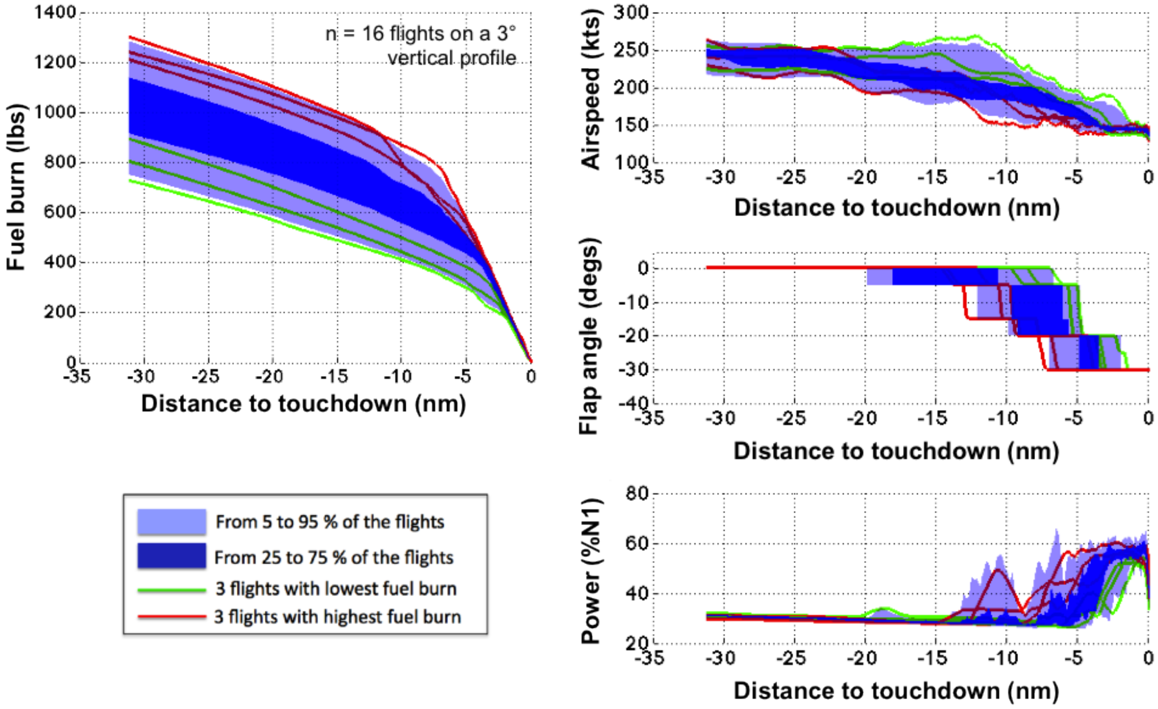
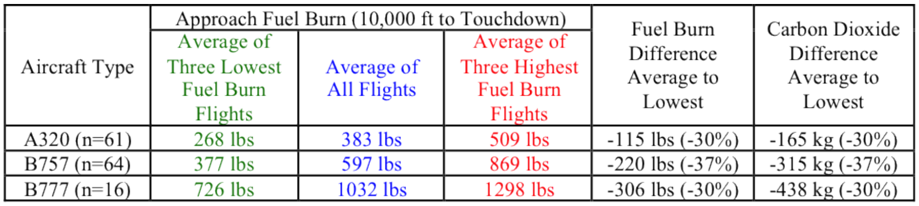


Figure 2-13: B777 Profile Results

differences between types in the 5-95th percentile zone, with the A320 exhibiting the largest variation. By contrast, the 25-75th 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 consistently the “high” side of the airspeed and flap setting profiles (i.e. delaying deceleration and flap deployment until later in the approach) and maintaining 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.

2.2.3 Observed Fuel Burn Saving Potential



Aircraft Type	Approach Fuel Burn (10,000 ft to Touchdown)			Fuel Burn Difference Average to Lowest	Carbon Dioxide Difference Average to Lowest
	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 (-30%)
B757 (n=64)	377 lbs	597 lbs	869 lbs	-220 lbs (-37%)	-315 kg (-37%)
B777 (n=16)	726 lbs	1032 lbs	1298 lbs	-306 lbs (-30%)	-438 kg (-30%)

Table 2.5: Approach Fuel Burn Summary

A summary of the fuel burns of these flights relative to the average across all flights is presented in Table 2.5, together with carbon dioxide emission estimates based on the standard relationship of 1 kg of fuel burn results in 3.16 kg of carbon dioxide emissions production.

The results suggest that flights whose characteristics are consistent with the philosophy of delayed deceleration and flap deployment correspond to 30-37% fuel and carbon dioxide 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.

2.3 Correlation Analysis

2.3.1 Correlation Matrix

The correlation coefficients between all parameters identified in Section 2.1.5 have been generated in a matrix form through the calculation of the covariance matrix ($R(i,j) = \frac{C(i,j)}{\sqrt{C(i,i) \cdot C(j,j)}}$, where R is the correlation coefficient between parameter i and j and C is the covariance matrix) for each of the aircraft types studied. Note that these matrices are symmetric ($R(i,j) = R(j,i)$) so that the lower triangular matrices as presented in Figure 2-14 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 as very poor correlations and are not shown (empty cells in the figure). The coloring of the cells indicates the strength of the correlation (as it is 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 R are written in the cell (the diagonal terms are only showing the self-correlation of each variable). The higher this value, the stronger 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 DFDR data for this aircraft type.

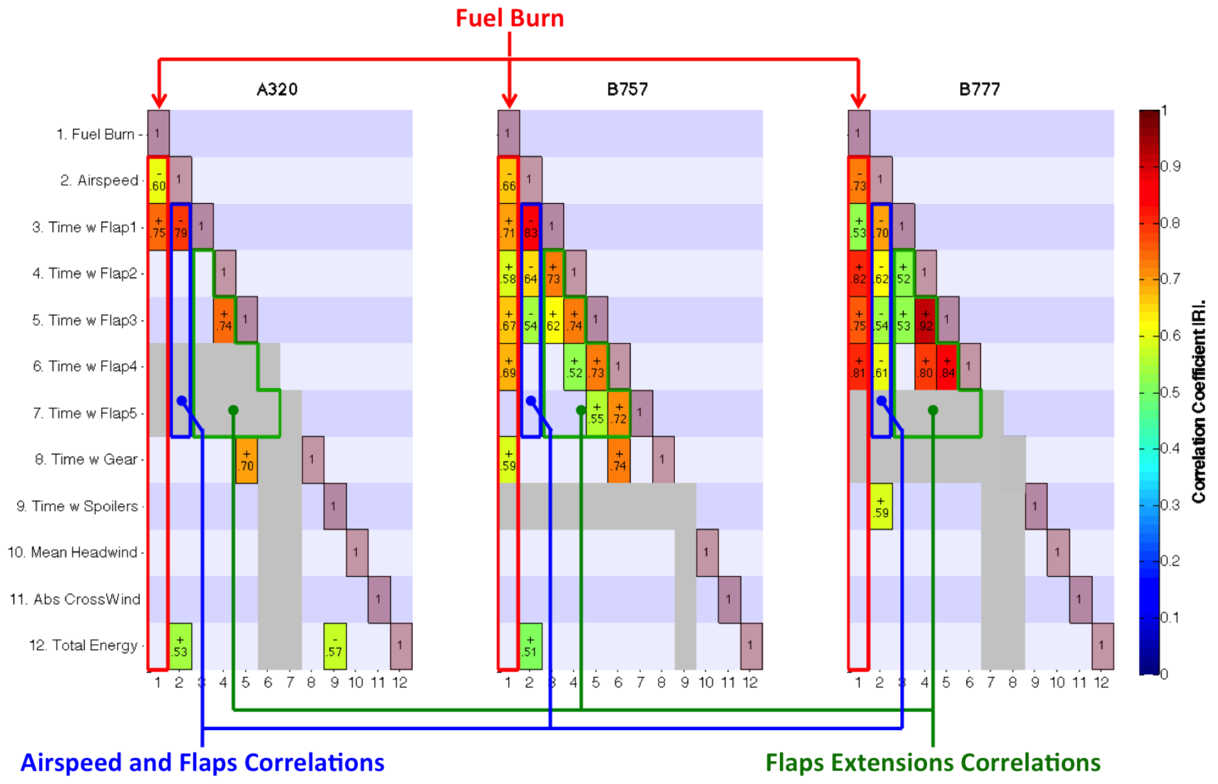


Figure 2-14: Correlation Matrices Showing only $R^2 > 0.25$ ($|R| > 0.5$)

The first column of each matrix, highlighted by a red contour box, represents the correlations of the total fuel burn during descent (from 10,000 ft to touch down) 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 proves that, despite the variability that exists in these parameters, they have no direct sizable 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 as 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. In addition, fuel burn strongly correlates with time flown with various degrees of flap extended, 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). This shows that fuel burn is mostly affected by airspeed and time flown with flap extended.

Another interesting correlation that is consistent across aircraft types is that of airspeed with time flown with flaps extended, highlighted by a blue contour box. 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 also correlates with airspeed for the B757 and B777 but to a lower extent. This means that when flights were slow during approach (relative to the distribution), they spent a longer time with their first degree of flap extended. Although that sounds logical, a lower correlation could have been expected following the argument that slow aircraft would still try to remain above the minimum speed for flaps extension to save fuel. Possible explanation for these early decelerations below flap extension speed could come from air traffic control imposing a slow airspeed or pilots configuring the aircraft early following some procedure for instance.

Another set of correlations that were expected were those of successive flap extensions, highlighted with a green box. These demonstrate similar sequence of extension of the flaps, especially after the first extension. In fact, it is visible from the distributions presented in Figures 2-11, 2-12 and 2-13 that the last flap extensions all happen in a fairly tight region. The correlation of gear extension with flaps for the A320 and the B757 (gear position from the B777 was not available) most likely indicates a procedure consisting of extending the gear simultaneously with this flaps setting.

This suggests that the later part of the decelerations are fairly similar across flights, but that the main differentiator is the first part of the deceleration, during which a first extension of flaps was necessary.

The remaining significant correlations are that of total energy 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 appendix.

In conclusion, this statistical study showed that fuel burn most strongly correlates with airspeed and time flown with flaps extended, but no significant correlation (i.e. with $R^2 \geq 0.25$) were found with winds or external energy. In other words, the variations in fuel burn that were previously observed are mostly attributable to differences in the airspeed and flap extension schedules, and not to differences in external factors.

A further exploration of the correlations of fuel burn with the deceleration schedule is presented next.

2.3.2 Correlation of Fuel Burn with Deceleration Schedule

The primary factors explaining the variation in fuel burn and identified from the correlation matrices presented above were airspeed and flaps extensions. These correlations are analyzed in more details in the following subsections.

2.3.2.1 Airspeed

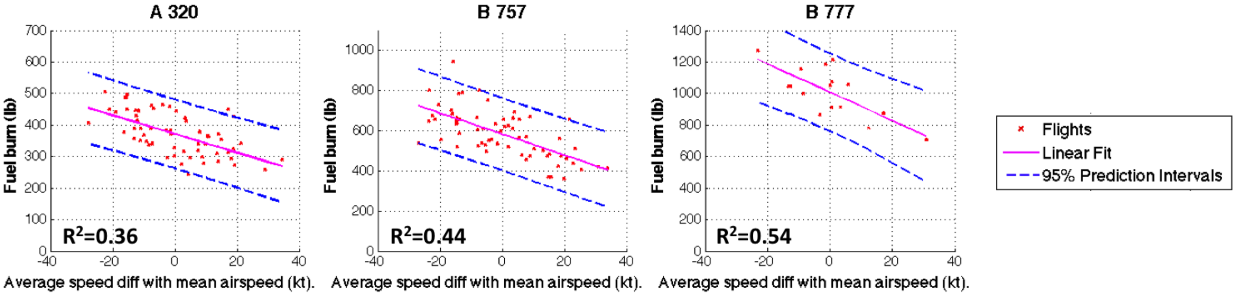


Figure 2-15: Correlation of Fuel Burn with Airspeed

Figure 2-15 shows the fuel burn versus the average airspeed difference with the mean of the airspeed distribution. 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 correlate with low fuel burns.

2.3.2.2 First Flap Extension

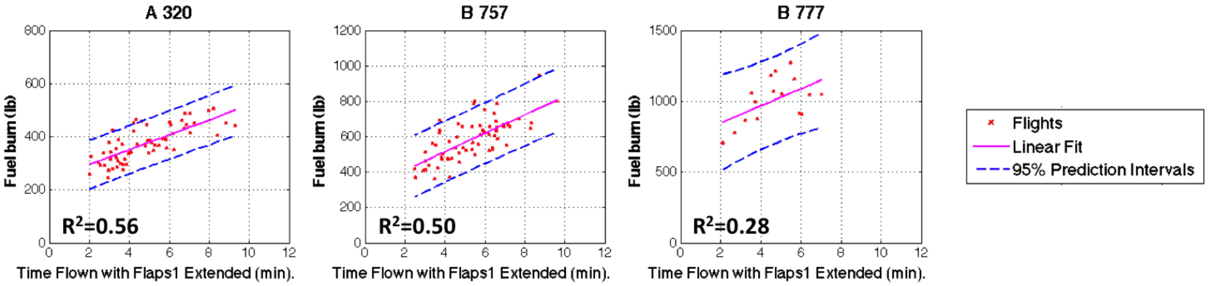


Figure 2-16: Correlation of Fuel Burn with Time Flown with Flaps 1 Extended

Figure 2-16 shows a similar degree of correlation between fuel burn and time flown with first flaps extended. This time, the slope is positive since the longer flaps were extended, the longer a higher fuel flow was necessary which results in a higher fuel burn. Similar correlation plots between fuel burn and the other degrees of flap extension are provided in appendix.

These results reinforce that the DDA 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.

2.4 Benefits Extrapolations

The results presented in the previous section demonstrate that flights with DDA characteristics hold significant promise for fuel burn reductions. This section applies the preceding results to assess how these aircraft-level potential benefits might impact system-wide fuel burn under two simple scenarios.

2.4.1 System-Wide Benefit Pool Estimate

From the DDA fuel burn potential identified with the DFDR data, it is possible to extrapolate the benefit pool estimate, i.e. the overall savings that the implementation of DDAs across the US would generate. Such an evaluation is a higher end of what can be achieved with DDAs since it assumes that all flights would be able to manage to keep their speed high within the same context of operations.

In order to get a sense of the US system-wide potential impact of DDAs, a correlation of DDA fuel savings as a function of aircraft maximum gross take-off weight (MGTOW) has been determined based on the FDR-based data points shown as diamonds in Figure 2-17. 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 2-17 was then used to estimate DDA fuel savings for aircraft in each aircraft class.

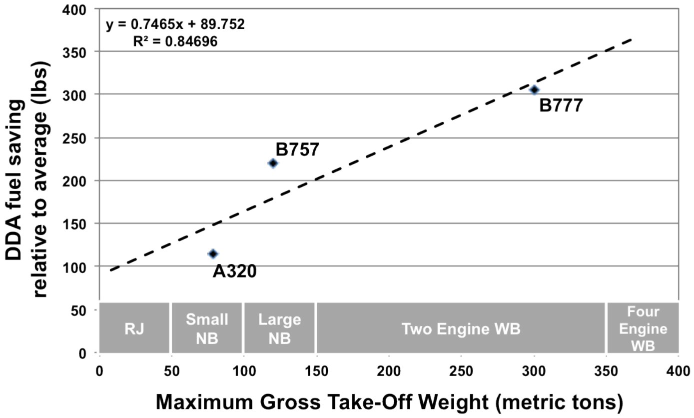


Figure 2-17: DDA Estimated Fuel Savings as a Function of Aircraft MGTOW

Operational data was used to determine the proportion of flights of each class operating in the US. From this, a DDA 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 DDA approaches, as shown in Table 2.6. The estimated fuel saving benefits pool is 5.3 million lb 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.

Aircraft Class	Example Aircraft Types	Represent-ative MGTOW (metric tons)	Estimated DDA Saving Per Approach (lbs)	Approx. Number Flights Per Day	DDA Fuel Reduction Benefits Pool (lbs/day)	DDA Fuel Burn Reduction Benefits Pool (US gallons/year)	DDA CO_2 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
			TOTALS	**30,000**	**5.3 million**	**290 million**	**2.8 million**

Table 2.6: US Flight Count by Aircraft Class

In reality, not all flights can fly DDAs due to various implementation barriers. The proportion of approaches that are able to conduct DDA 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 DDA operations with fuel reductions suggested by Figure 2-17, 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.

2.4.2 Representative Airline Savings

Another example of potential fuel savings is that of an airline with a fleet of 100 Boeing 757s, where each aircraft would conduct a single DDA per day (achieving 220 lb fuel saving per flight as identified in Table 2.5). This would result in savings of 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 11,500 metric tons lower carbon dioxide emissions per year.

2.5 Conclusions

The study of operational DFDR data has evidenced the relationship between speed schedule and fuel burn consumption during approach. The most efficient flights have been seen to decelerate and extend their flaps late in approach, while the least efficient flights spent long periods of time at low airspeed and with flaps extended. In addition, a correlation analysis identified airspeed and time flown with flap extended as the main correlations with fuel burn.

For flights on a three-degree descent profile between 10,000 ft and touch down, fuel burn savings of 30 to 37 % are suggested. This provides very promising savings if DDAs could be generalized system-wide.

The implementation barriers which need to be overcome to enable DDA savings to become a reality are discussed in the next chapter.

Chapter 3

System Level Analysis

Despite the significant fuel saving potential identified in the previous chapter, the analysis of the flight data also showed that most flights were not flying Delayed Decelerations Approaches, thus resulting in higher approach fuel burns than ideal. The purpose of this chapter is to explore potential reasons why many flights decelerated early and to identify opportunities for wider use of DDA in the operational environment so that more flights could benefit from the fuel burn and emission reductions these profiles may enable.

3.1 Identification of Potential Barriers to Implementation

3.1.1 Overview

Potential barriers to implementation have been identified from discussions with key stakeholders - namely, airlines and air traffic controllers. These could be segregated into two categories: those which deal with the handling of the aircraft, which are the responsibility of the pilot; and those that come from the air traffic operations, which are managed by the air traffic controllers.

3.1.2 Aircraft Operations

Pilots are responsible for the safe evolution of the flight, and in particular they must ensure that the plane is fully configured and ready for landing at the stabilized approach point ($1,000\ ft$ or $1,500\ ft$ (depending on the airline) above the airport elevation on a 3 degree descent profile).

The decision of the airspeed schedule is hence mostly determined by training and by the airline Standard Operating Procedures (SOPs). However, other factors may also play a role; for instance, uncertainty in remaining distance before touch down or reluctance to use spoilers.

3.1.2.1 Airline SOPs

It is unclear whether the fuel burn reduction potential of DDAs is fully appreciated by all airlines. Some airlines have clearly demonstrated their interest for fuel savings during descent with full scale trials and implementations of new technologies to reduce vertical and horizontal efficiencies; amongst others are optimization of altitude profile with CDAs [9], tighter spacing between aircraft on arrival using ADS-B [16], or optimization of standard routes from origin to destination airports accounting for weather and other factors [17, 18]. More generally, fuel savings and noise reduction have been the main motivation of the development of new approaches recently.

However, literature is more scarce about the effects of modifying the speed profile during descent. Discussions with some airlines have nonetheless shown their interest in integrating DDAs in current and future procedures. For instance, some of them are issuing guidelines of speed targets as a function of distance to touch down (e.g.: maintain at least 190 KT to 12 nm to touch down), or creating a full deceleration schedule by recommending airspeeds for various distances away from touch down. Although these are mainly motivated by noise reduction, they suggest later deployments of high-drag devices (e.g.: extend gear 2000 ft above ground level or later); which was also mentioned in a Boeing's series of article on fuel conservation strategies [14].

Although the discussions with airlines did not conclude in a clear answer as to their willingness to train their pilots to delay the deceleration, they also highlighted practical issues that pilots are confronted with and which affect their speed profile decisions. These are detailed in the next paragraphs.

3.1.2.2 Uncertainty in Distance to Touch Down

An interesting case happens when aircraft do not arrive straight in on final but have a portion of down wind (flight away from the airport prior to turning into the wind for final approach). In this case, pilots may not be informed of the time the traffic controller intends to turn them onto final; in other words, the pilots may not know how much distance remains to be covered before touch down. This is illustrated in Figure 3-1.

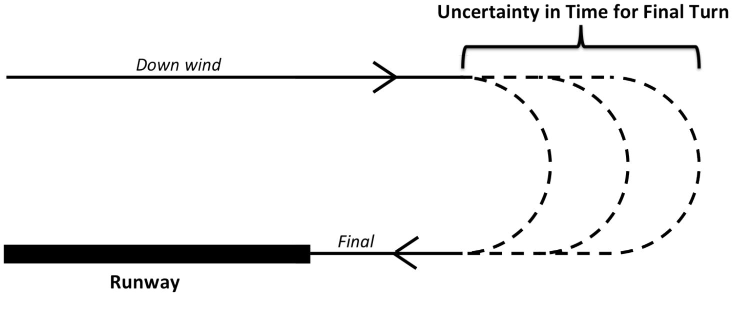


Figure 3-1: Illustration of Uncertainty in Distance to Touch Down

This situation prevents the use of speed targets recommendation as a function of distance to touch down as described earlier, because the exact value of the distance remaining is unknown. In this situation, pilots will most likely prepare the aircraft based on the shortest possibility of turning onto final since this would allow them to land the aircraft in all situations. In fact, if the aircraft were too high and or too fast when asked to proceed to final, the approach may result in a costly go-around.

Therefore, in that case the aircraft may fly a longer amount of time with a slower airspeed than ideal in terms of fuel efficiency. This same issue is a challenge to the execution of CDAs, but modified ATC procedures have been developed where ATC gives the pilots an estimate of distance to go so they can manage their vertical profiles, which would also help with speed management to deliver more efficient DDA profiles.

3.1.2.3 Use of Spoilers

There also seems to be a common bad perception in the pilot community with respect to the usage of spoilers. In fact, unless made necessary by aggressive speed or altitude reduction mandated by air traffic controllers, the use of spoilers seems to be considered as an indicator of poor technique by many pilots. This may encourage pilots to decelerate earlier than ideal so as to reduce the risk of needing spoilers. This applies in particular when the exact remaining distance to touch down is unknown, as described earlier.

Theoretically speaking, spoilers may be needed in some occasions when flying the optimum DDA profile to cope with potential uncertainties. For instance, if the headwind is less than what was expected from the weather forecast, extending some spoilers could bring the flight back to the optimum profile. By willingly refusing to use spoilers in all situations, the pilots must add a margin compared to the optimum profile to absorb the uncertainties of the situation. This results in lower fuel efficiency than optimum.

3.1.2.4 Other Factors

There are a number of other factors at the aircraft level that may motivate early deceleration. For instance, severe weather conditions (strong lateral winds, turbulences, low visibility, etc.), complicated vectoring procedures (aircraft vectored around thunder-storms, or around other flows of aircraft, etc.), aircraft partial dysfunction, or other factors that increase the pilots workload, are likely to motivate pilots to slow down early, since this would give them more time for handling the situation.

However, the main focus of this study of barriers to implementation has been on air traffic operations, which are believed to have the greatest effect on fuel efficiency.

3.1.3 Air Traffic Operations

Air traffic operations concern the organization and management of the airspace so that it can be safely used by all flying vehicles. As such, pilots have to conform to Air Traffic Control (ATC) clearance, with the potential effect of increasing their fuel burn relative to the unimpeded case. In particular, and for the domain of application of this research, the main potential barriers to flying fuel-efficient DDAs are air traffic congestion, restrictions from specific air traffic procedures and air traffic controller technique.

3.1.3.1 Air traffic congestion

Air traffic congestion happens at times when the demand for landings at an airport is close to or exceeds the capacity [19]. This may happen during rush hours or hub arrival times at busy airports, when expected arrival times are bunched together. Even when demand is lower than but reasonably close to the capacity, different sources of variability (e.g., rate at which aircraft enter the TRACON, aircraft mix in the arrival flow, wind, etc.) may lead to significant delays and congestion around the airport. In addition, unfavorable weather conditions (thunderstorms, winds, low visibility, extreme precipitations, etc.) decrease the capacity of airspace/airport and impose additional constraints which can result in congestions and delays.

In these situations, the high density of aircraft that need to be vectored to the approach may restrict the freedom in the airspeed schedule of each individual flight. In particular, if a dense flow of arrivals presents a mix of speed capabilities between aircraft, then the flow will generally have to match speed with the slowest aircraft to maintain separation distances. Such a situation may result in large aircraft having to decelerate and extend flaps much earlier during the descent than they would if they were not being impacted by flights ahead.

3.1.3.2 Specific air traffic procedures and airspace

Specific air traffic procedures may also dictate the airspeed in order to produce a very predictable flow of arrivals. Such a situation may arise in a metroplex where the flows of arrivals and departures are tightly interleaved, such as in the New York City area. In addition, having a slower flow of aircraft also provides more time to sequence them and may decrease ATC workload. Slowing aircraft down may thus be a decision motivated by safety when flights move in tight corridors during descent.

3.1.3.3 Controller Technique

In some occasions, air traffic controllers may assign a given airspeed to all aircraft on approach regardless of the intensity of the traffic for easier management of the traffic flow and lower workload. This could be for a number of reasons, such as standardizing the speed in the terminal area to increase predictability; reducing the speed of the fastest aircraft to have more time to process them; or habitually using a technique that works well for high density of arrivals even when the demand is low.

It is important to note that fuel efficiency during descent is generally not directly considered by air traffic controllers whose main priority is safety, followed by arrival throughput and keeping workload manageable[1]. However, by having a faster average airspeed during approach, DDAs also enable more flights to be processed in a given time and therefore increase the throughput, such that controllers may also benefit from applying DDAs through workload reduction by eliminating the need for complex holding operations.

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[1] However, there is increasing motivation to involve controllers in the effort of improving system-wide fuel efficiency. One example is the recently implemented rating on fuel efficiency for controllers in the UK air traffic control (NATS) [3]

3.2 Methodology to Assess Air Traffic Effects

3.2.1 Overview

In order to assess air traffic factors that may influence why some flights slowed down early and had higher fuel burns, air traffic operations surrounding aircraft in arrival have been analyzed. The methodology used in this chapter is designed to account for traffic flow effects as shown in Figure 3-2. It is based on fused radar track data (PDARS - Performance Data Analysis and Reporting System) for aircraft arriving into one airport or metroplex. This study was deliberately restricted to a given wake-vortex category: Large and B757 following other Large aircraft (common occurrences of Large aircraft are A320 family, B737s, CRJ200 and 700 series, Embraer E-jet family, amongst others) to provide a fair basis of comparison between aircraft performance. This category was chosen as it encompasses a large majority of all flights around busy airports.

The missing parameters from PDARS data such as airspeed and fuel burn efficiency are then estimated, and are combined with the calculation of separation distances with other aircraft (indicating where other traffic around an aircraft was located) to assess the potential for DDAs. These steps are detailed in the following sections.

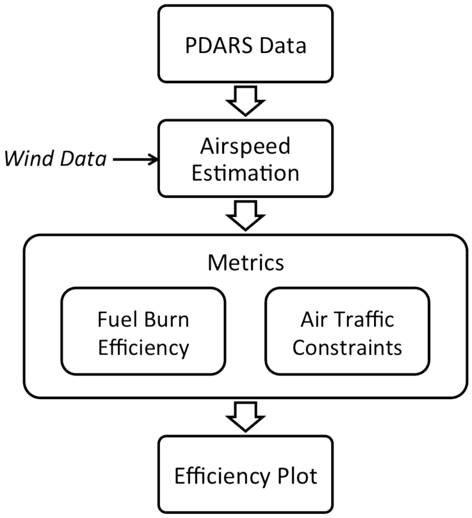


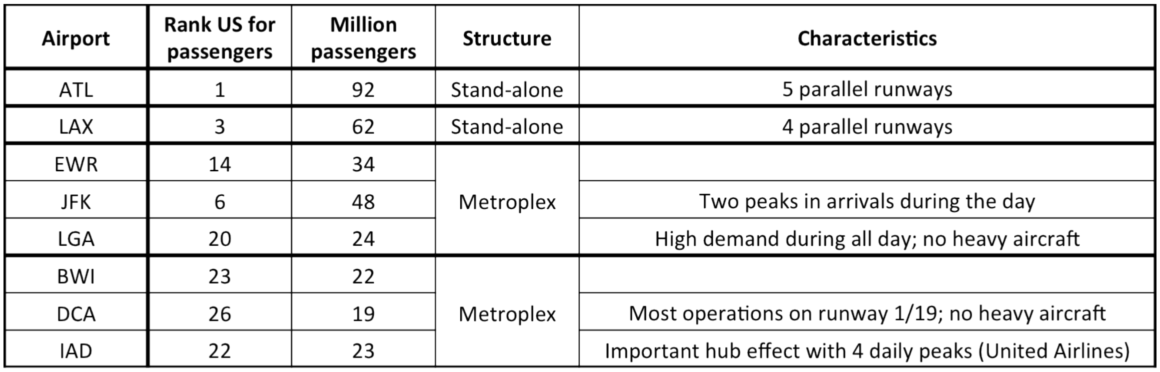
Figure 3-2: PDARS Analysis Methodology

3.2.2 PDARS Data

PDARS data provide fused radar track data giving geographical coordinates of all airborne aircraft at a sample rate of approximately 5 seconds in terminal areas and 12 seconds outside, along with their flight identifiers and aircraft types. However, PDARS data do not contain weather information or internal information about the aircraft such as airspeed or fuel burn, which are of prime importance for this study.

Airports Selection Eight airports were chosen for the analyses. Two of them were stand-alone airports: Atlanta (ATL) and Los Angeles (LAX); no other major airport directly affect their operations[2]. The remaining six airports belonged to two metroplexes: Newark (EWR), Kennedy (JFK) and La Guardia (LGA) are the three busiest airports serving New York City; while Baltimore (BWI), Reagan (DCA) and Dulles (IAD) are the three airports serving the Washington DC area. Illustrations of the organization and runway configuration of the airports of the study are given in Figure 3-3.

Their rankings in terms of number of passengers for the year 2011 (source: Airports Council International) as well as some main characteristics are provided in Table 3.1. Atlanta is the biggest airport in the world in number of passengers, which is made possible by a fairly simple structure of 5 parallel runways. Los Angeles has roughly two thirds of the amount of passengers compared to Atlanta with four parallel runways. It is interesting to see that the total number of passengers going through the New York metroplex (3 airports, 9 runways) is comparable to that of Atlanta (1 airport, 5 runways). In fact, the strong interactions between the departures and arrivals at each airport in the metroplex limits the overall number of operations. Finally, the Washington DC metroplex is clearly less intense than that of New York, with a total number of passengers of 64 million passengers, which compares to that of Los Angeles.



Airport	Rank US for passengers	Million passengers	Structure	Characteristics
ATL	1	92	Stand-alone	5 parallel runways
LAX	3	62	Stand-alone	4 parallel runways
EWR	14	34	Metroplex	
JFK	6	48		Two peaks in arrivals during the day
LGA	20	24		High demand during all day; no heavy aircraft
BWI	23	22	Metroplex	
DCA	26	19		Most operations on runway 1/19; no heavy aircraft
IAD	22	23		Important hub effect with 4 daily peaks (United Airlines)

Table 3.1: Main Airport Characteristics (data for year 2011)

Nevertheless, all these airports have a high number of traffic operations (they are amongst the 30 busiest airports in the US) and hence represent a significant potential for fuel burn benefits as well as potential existence of barriers to DDA implementation. In addition, their structural and operational differences may provide some insights into which characteristics of an airport configuration most affect the potential for DDAs.

Days of data The available PDARS data consists of six different days of operation for each of the four locations, except New York area for which only five days were available. These are listed in Table 3.2.

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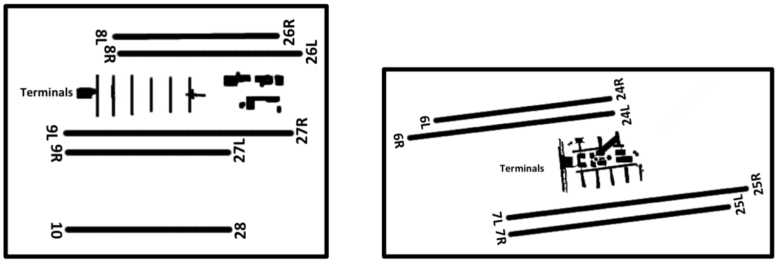
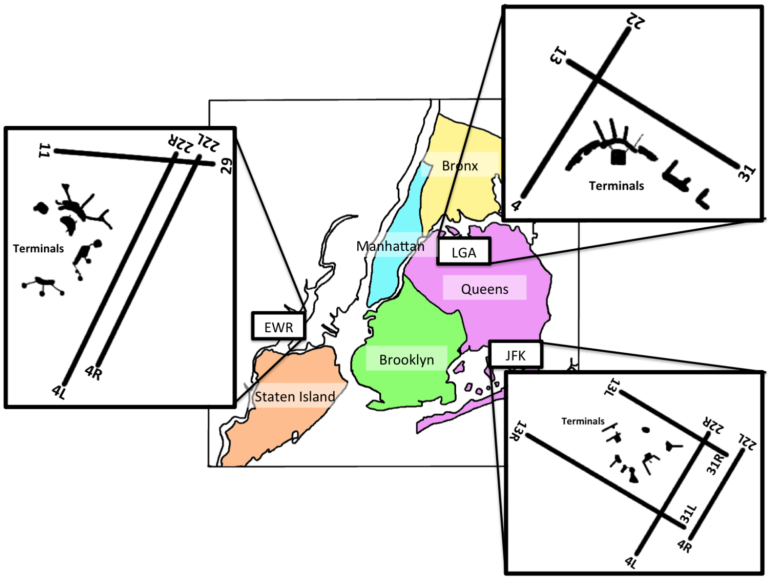
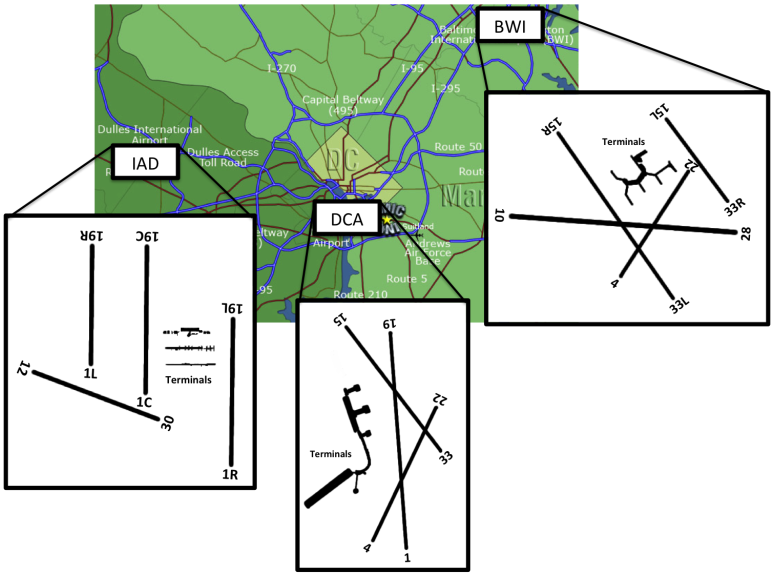
[2] In fact, LAX is technically in a metroplex, but as major component of that metroplex priority is given to the flows to that airport, such that it can be considered as a stand-alone airport with a good approximation.



(a) Atlanta (b) Los Angeles



(c) New York City Metroplex



(d) Washington DC Metroplex

Figure 3-3: Illustrations of Runway Configurations

Los Angeles (LAX)	Atlanta (ATL)	New York (EWR, JFK, LGA)	Washington DC (BWI, DCA, IAD)
Sun 02/24	Fri 02/22	Tue 02/05	Thu 01/17
Wed 06/18	Sun 04/06	Wed 03/19	Sat 03/08
Fri 07/18	Thu 06/26	Mon 03/31	Sun 05/11
Mon 08/04	Thu 07/10	Mon 06/23	Sat 06/14
Wed 08/13	Sun 07/13	Wed 07/23	Sat 07/05
Sat 09/27	Mon 08/25		Tue 09/30

Table 3.2: Available PDARS data by location

3.2.3 Airspeed Estimation

Airspeed is a critical parameter to determine when and how decelerations occurred. However, radar tracks only provide ground speed through the calculation of incremental distance covered over an increment of time. Therefore, historical wind data from the National Climatic Data Center (NCDC) were used to correct groundspeed for wind speed and hence estimate airspeed profiles from the PDARS position data. These wind parameters were provided on a grid of roughly 32 km by 32 km in increments of 1,000 ft and every 3 hours. Winds were interpolated between these points along each flight track and combined with the ground speed to generate the airspeed estimates.

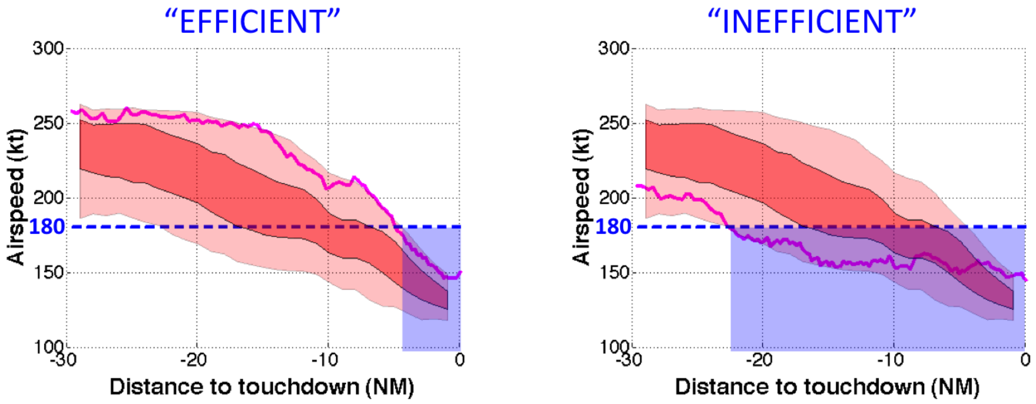
3.2.4 Metrics

3.2.4.1 Metric for Fuel Burn Efficiency

Description A high correlation between fuel burn and time below first flap extension speed has been observed in Section 2.3: a longer time spent with flap extended correlates with a higher fuel burn. In other words, the fuel burn efficiency of one approach evolves as the inverse of the time spent with flaps extended. This is illustrated for an Airbus A320 in Figure 3-4, where the airspeed for first flap extension was 180 kts.

The airspeed profile on the left is that of a DDA, with only 2 minutes of flight below first flap extension airspeed (180 kts), which is considered to be fuel “efficient”. The profile on the right shows an early deceleration, resulting in a much longer time (8 minutes) below 180 kts and hence in a high drag configuration. This latter approach is considered rather “inefficient” in terms of fuel burn, because it required a higher thrust setting for longer than ideal to compensate for the increased drag. Note that there is no specific value that qualifies an approach as efficient or inefficient; however these terms will be used to qualify the most efficient flights compared to the least efficient ones.

As a consequence, the time spent below the flap extension speed that is observable from the wind corrected PDARS data has been used for this study as an indicator of the fuel burn efficiency of a given flight.



Time spent below 180kt: 2 mins

Time spent below 180kt: 8 mins

Figure 3-4: Illustration of Efficiency Measured by Time Spent Below First Flap Speed

3.2.4.2 Metric for Air Traffic Constraints

The metric used to assess air traffic constraint was the closest separation distance with the preceding aircraft on the arrival flow to a given runway, as illustrated in Figure 3-5.

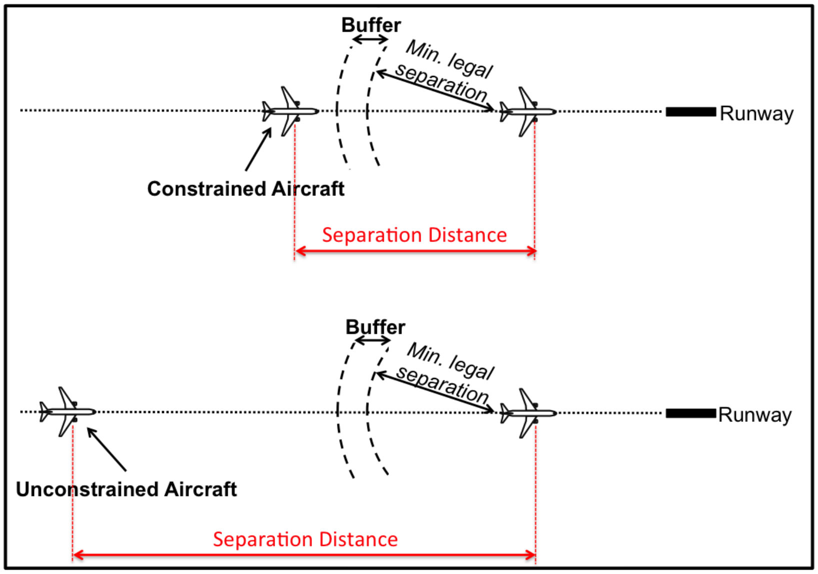


Figure 3-5: Illustration of Traffic Constraints

If an aircraft desired to delay its deceleration until later in its approach, it would need to have sufficient separation distance with the aircraft ahead of it to ensure no aircraft separation violations would occur (unless the aircraft ahead also sped up). Measuring this separation distance gives an estimate of the amount of freedom in airspeed an aircraft had.

The wake vortex separation requirements vary by weight category of the leader and follower aircraft in the pair (i.e. Small, Large, B757, Heavy, Super-heavy). For the Large and B757 following Large wake vortex category considered in this study, the separation standards set the minimal separation distance to 2.5 nm in Instrumental Meteorological Conditions (IMC)[3], as shown in Table 3.3. Although not a legal requirement, we will also consider the same distance for Visual Meteorological Conditions (VMC) to quantify air traffic constraints.

		Leading aircraft			
	(NM)	H	B757	L	S
Trailing aircraft	H	4	4	2.5	2.5
	L+B757	5	4	2.5	2.5
	S	6	5	4	2.5

H: Heavy
- B747, B767, A300
L: Large
- B737, A320, CRJs
S: Small
- GA, business jets

Table 3.3: IFR Wake Vortex Separation Requirements

The fact that the study was restricted to a given wake-vortex class conveniently offers a common reference for the minimum separation distance; in addition, aircraft speed performance are fairly similar in that category which also enables using a single airspeed as first flap extension speed with good approximation. It was then assumed that flaps were extended at least up to their first position when an aircraft of the Large or B757 category passes below 180 kts.

3.2.5 Efficiency Plot

The potential DDA opportunity for each flight was assessed by plotting the fuel efficiency, represented by the time spent below the first flap extension speed as a function of the throughput efficiency, embodied by the minimum separation distance with the preceding aircraft. This representation has proved very useful to quickly assess the potential for DDA and has been essentially used for Section 3.4.

Figure 3-6 presents an example of efficiency plot for one hour of operation at La Guardia (between 11:00 and 12:00 on Wednesday 23rd, July 2008), when runway 22 was used for all arrivals. Each blue cross represents one occurrence of a Large or B757 following another Large in arrival.

The red annotations have been added to highlight specific regions of the efficiency plot. First, region A includes flights which had little separation with the preceding aircraft but which still managed to maintain a high airspeed and spend little time below 180 kts. These represent a fast and dense flow of arrivals, which maximizes both fuel and throughput efficiencies. Most aircraft in Figure 3-6 were around that region, some aircraft being less fuel efficient even though they might have had more spacing with the preceding aircraft. However, point B represents an aircraft that was quite constrained (in the sense that it had low separation distance with the preceding aircraft), but which spent a lot of time below 180 kts with flaps extended. This aircraft was possibly in a flow of aircraft following a smaller aircraft (e.g. turboprop) and all had to match speed with it not to get too close to the preceding aircraft, or perhaps the pilots decided to decelerate early for another reason. The opposite behavior is that of point C, for which the aircraft had high separation

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[3] 2.5 nm separation is used at the busiest airports in the United States. Smaller airports may use 3 nm but these are not included in this study.

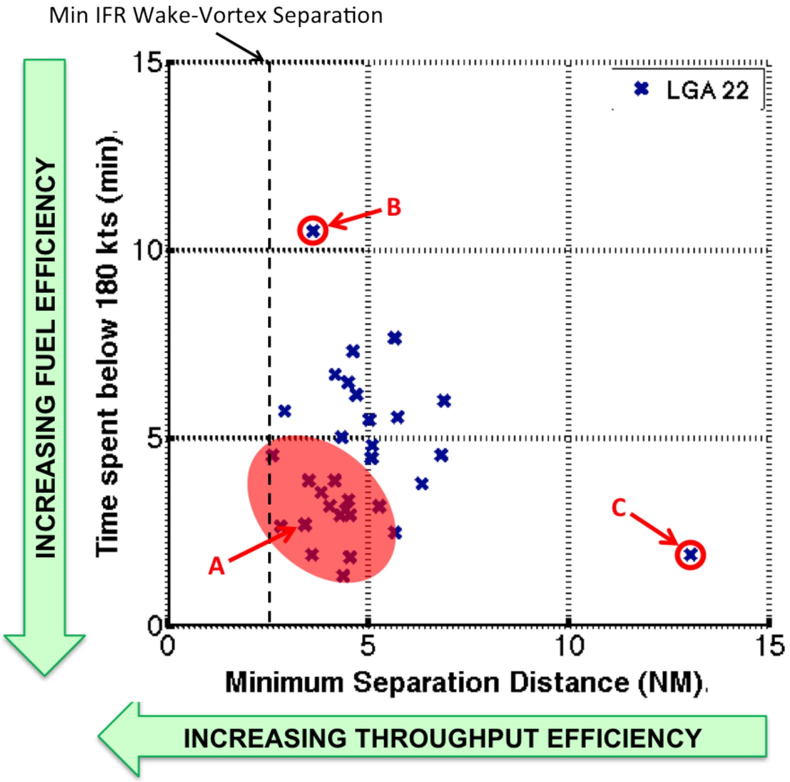


Figure 3-6: Example of Efficiency Plot for 1 Hour of Operations at La Guardia

distance and maintained high airspeed during most of the descent. This is the behavior that would be expected when separation distances are high.

This example shows how the efficiency plot enables assessment of fuel efficiency while comparing it to the degree of constraints generated from preceding aircraft. More insights obtained from the efficiency plot are discussed in Section 3.4. In addition, a more conceptual description of the different regions in the efficiency plot is provided in appendix.

3.3 Overall Performance Assessment

Before presenting detailed observations of the operations illustrating potential for increased DDAs, high-level performance assessment of the data by airport has proven useful to distinguish the modes of operation of the different locations.

3.3.1 Overview

3.3.1.1 Fuel Efficiency

Figure 3-7 shows the cumulative distribution of the total time flown below 180 kts for aircraft of the wake-vortex class Large + B757 following Large at the eight different airports. In order to maximize the fuel efficiency, a high proportion of flights spending little time below 180 kts (high drag configuration) is desirable; that is, fuel efficiency is maximized as curves move closer to the upper left part of the plot.

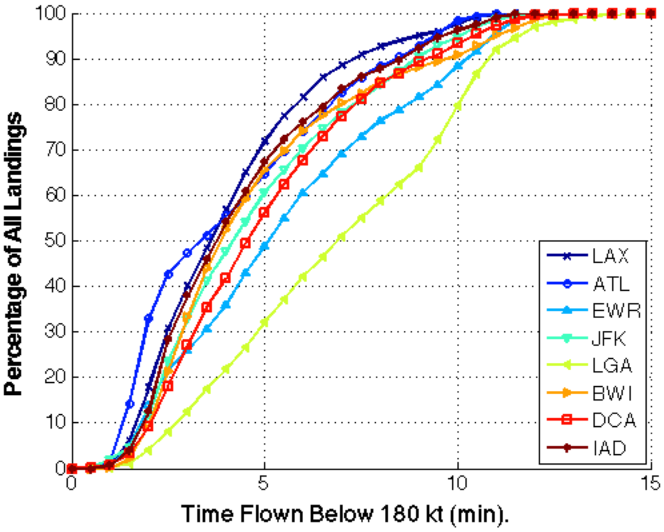


Figure 3-7: Cumulative Distributions of Time Below 180 kts at the Four Locations (Eight Airports)

Figure 3-7 shows that Newark and especially La Guardia turn out to spend more time below 180 kts than the other locations which have fairly similar trends. This may indicate that high density of arrivals and the added complexity from operating in a dense metroplex like New York favors early decelerations in approach.

Another observation from this plot is that Atlanta stands out for having a much higher proportion of flights with little time spent below 180 kts, indicating that there are more very efficient approaches there than at the other locations. For instance, 43% of the flights spent less than 2.5mins below that speed; the corresponding proportion for the other locations would be between 18 and 31 %, except for La Guardia for which it would be only 8%. This seems to indicate that controllers at Atlanta try to have aircraft fly faster, possibly to enable higher throughput and satisfy the high demand at that airport. However controllers at New York airports could be expected to have the same motivations, given the similarly high demand. It is possible that the complexity in New York airspace has led to practices of early speed reductions to lower the controllers workload, which would explain the lower overall fuel efficiency experienced at New York. More details by airports are given in the following sections.

3.3.1.2 Air Traffic Constraints

Figure 3-8 shows the cumulative distributions of the Minimum Separation Distance for all aircraft belonging to that same wake-vortex category; the dashed vertical line at 2.5 nm is the minimum legal Instrument Meteorological Conditions (IMC) wake vortex separation distance; aircraft may fly closer than that value, but only in Visual Meteorological Conditions (VMC). The throughput increases as the separation distances decreases; such that throughput efficiency increases as the curves get closer to the upper left part of the plot.

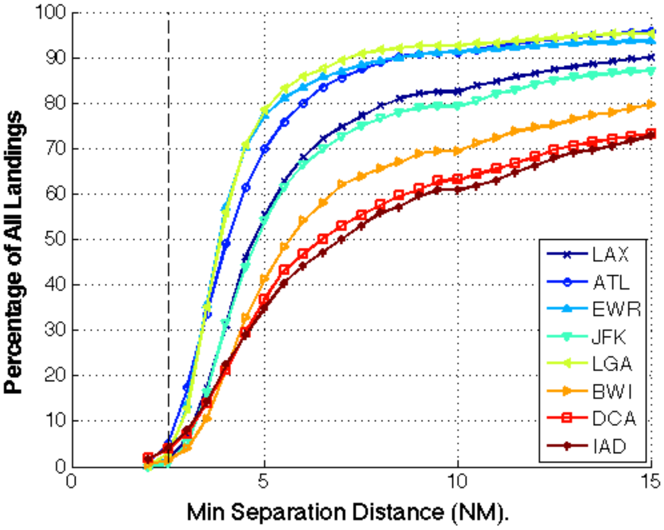


Figure 3-8: Cumulative Distributions of Separation Distances at the Four Locations

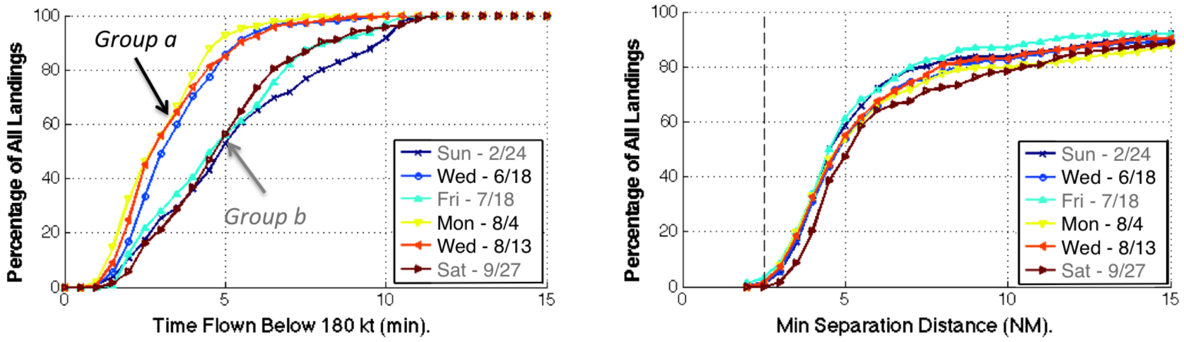
Figure 3-8 clearly shows that the three airports from Washington DC metroplex (BWI, DCA and IAD) have higher separation distances than the other locations on average. Then Los Angeles and Kennedy airports present very similar curves. Finally, Atlanta, Newark and La Guardia are the airport with the closest separation distances in arrival. In particular, for Newark and La Guardia about 80 % of their flights have less than 5 nm of separation with the preceding aircraft; for the other airports, the corresponding proportions would be: 70% for Atlanta, 55% for Los Angeles and Kennedy, and between 34 and 42 % for the Washington DC airports.

This is consistent with the fact that Atlanta and New York have higher overall demand than the other locations, suggesting traffic flows are being run much tighter at these airports to maximize throughput. The fact that Newark and La Guardia have at the same time the shortest separation distances and the lowest fuel efficiency (see Figure 3-7) is probably not a coincidence. However, Atlanta managed much higher fuel efficiency with almost the same separation distances. This suggests that additional constraints from operating in a metroplex played a role in lowering the fuel efficiency at Newark and La Guardia.

For the next subsections of this overall performance assessment, the data has been further broken down by day of operation for each airport in order to observe the variability from one day to the other and to assess the potential effects of weather and other factors on the results.

3.3.2 Los Angeles

Figure 3-9a shows that the six days of data at Los Angeles behave according to two distinct behaviors in terms of fuel efficiency. The days in group a (Wed 6/18, Mon 8/4 and Wed 8/13) are much more fuel-efficient than the days in group b (Sun 2/24, Fri 7/18 and Sat 9/27). In particular, about 90% of the flights in group a spent less than 5 minutes below 180 kts, while only 55% of the flights in group b are in this situation.



(a) Distribution of Time Flown Below 180 kts (b) Distribution of Minimum Separation Distance

Group a

Week day	Date	Overall Weather		Scheduled Operations	% on-time Arrivals
		Value	Impact		
Sun	02/24	0.15	None	1630	54
Wed	06/18	0.0	None	1725	81
Fri	07/18	0.33	Minor	1767	81
Mon	08/04	0.00	None	1745	82
Wed	08/13	0.05	None	1734	85
Sat	09/27	0.23	None	1256	86

(c) Overall Weather

Figure 3-9: Overall Performance at Los Angeles

If the air traffic constraints were a major factor resulting in the differences in fuel burn efficiency between group a and b, then distributions of minimum separation distances should also exhibit two groups of curve, with the shortest separation distances corresponding to the worst fuel efficiencies. However, Figure 3-9b shows that the six days of data have very similar behaviors of separation distances between the flights. In particular, only roughly 60% of the flights had a separation distance lower than 5 nm (twice the requirement), which means that a significant proportion of the flights had very little constraints from a preceding traffic. This shows that the air traffic constraint did not seem to play a significant role in the fuel burn efficiency at LAX for the days of data available.

The weather situation for each day of data at Los Angeles is summarized in Figure 3-9c, where the days corresponding to group a have been highlighted in blue. All values were obtained from Aviation System Performance Metrics (ASPM), which is a tool developed by the FAA for efficiency analyses; the value under "Overall Weather" represents an aggregate score of how much each operation (aircraft arrival or departure) was affected by the weather (the higher the value, and the higher the effect). This table shows that all days had good overall weather conditions (either none or minor impact); a notable difference between the days would be the lower number of scheduled operations on Sat 9/27. This is consistent with the slightly higher separation distances for that day from Figure 3-9b (curve slightly shifted to the right), but then that day would be expected to have higher fuel efficiency if the air traffic was the main constraint. However that day was observed to belong to group b, the lower efficiency group, suggesting that other factors played a role in the fuel efficiency.

The number of departures and arrivals as a function of time of the day are shown in Figure 3-10. The top plot clearly shows the opening of the airport and start of operations at 6:00, followed by a roughly constant rate of operations with about 50 departures and arrivals (bottom plot) per hour. Departure rate decreases as the day goes by, probably due to the night that starts to set in the rest of the country. At the same time, arrival rate goes slightly up until 21:00.

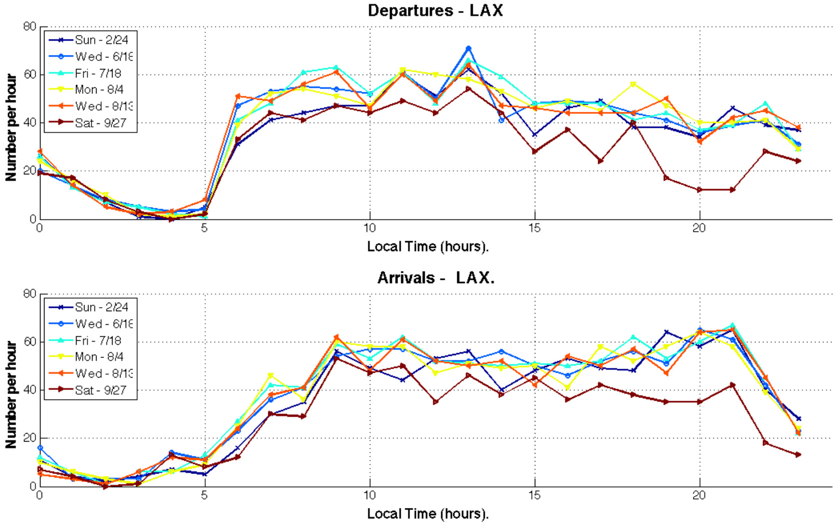
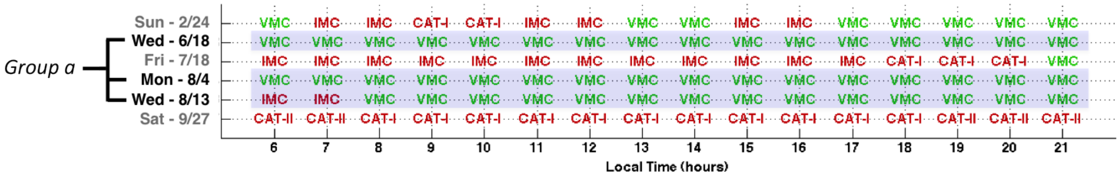


Figure 3-10: Number of Departures and Arrivals at LAX

This plots shows that apart from Saturday 9/27, known to have less traffic volume, all days of data had very similar trends of operations as a function of time of the day. This similarity in traffic volumes further reinforces the hypothesis that something else (not observed so far) influences the fuel efficiency.

More valuable insight were gained by looking at the meteorological condition during the busiest hours of the day, between 6:00 and 21:00 (which includes about 90 % of the flights), as shown in Figure 3-11. VMC, IMC, CAT-I, CAT-II and CAT-III are visibility and ceiling conditions of increasing severity. The days under group a (the more fuel efficient) have been shaded in blue for easier identification. This shows that the most efficient days were almost entirely under VMC. Conversely, the other three days presented at least half of the period under more restrictive IMC/CAT-I/CAT-II conditions; Sat 9/27 being the worst day in terms of weather with CAT-I or CAT-II conditions only.



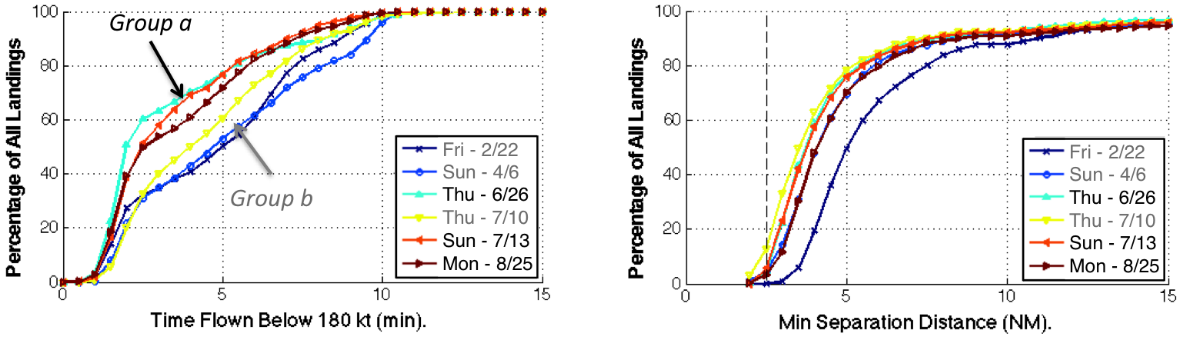
	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Sun - 2/24	VMC	IMC	IMC	CAT-I	CAT-I	IMC	IMC	VMC	VMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC
Wed - 6/18	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Fri - 7/18	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	CAT-I	CAT-I	CAT-I	VMC
Mon - 8/4	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Wed - 8/13	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Sat - 9/27	CAT-II	CAT-II	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-II	CAT-II	CAT-II

Figure 3-11: Meteorological Condition at LAX

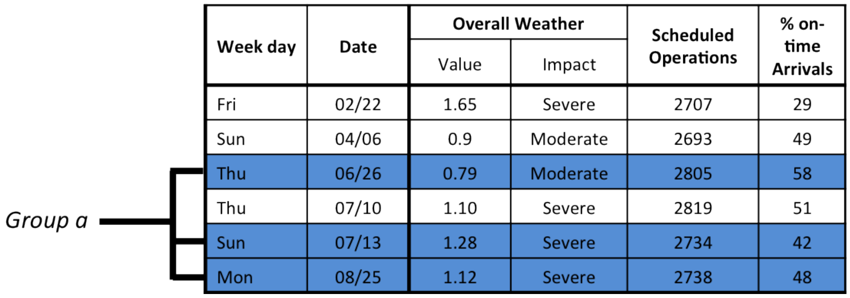
This seems to indicate a correlation between airport meteorological conditions and fuel efficiency. It is believed that this correlation comes from the fact that pilots decelerate and configure their aircraft for landing much earlier in IMC as part of an instrument landing procedure. On the other hand, they may wait for later decelerations in visual conditions in order to arrive faster to their destination.

In this analysis at Los Angeles, arrivals were seen to be most fuel-efficient during VMC, and the loss of efficiency observed during the days for IMC is most likely mainly attributable to the weather conditions. Comparisons with observations at other locations may further confirm this hypothesis.

3.3.3 Atlanta



(a) Distribution of Time Flown Below 180 kts (b) Distribution of Minimum Separation Distance



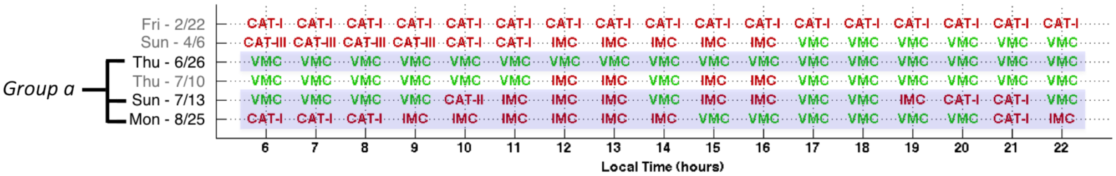
Week day	Date	Overall Weather		Scheduled Operations	% on-time Arrivals
		Value	Impact		
Fri	02/22	1.65	Severe	2707	29
Sun	04/06	0.9	Moderate	2693	49
Thu	06/26	0.79	Moderate	2805	58
Thu	07/10	1.10	Severe	2819	51
Sun	07/13	1.28	Severe	2734	42
Mon	08/25	1.12	Severe	2738	48

(c) Overall Weather

Figure 3-12: Overall Performance at Atlanta

Similarly to Los Angeles, the cumulative distributions of the time flown below 180 kts have been generated for Atlanta and are plotted in Figure 3-12a. Although the distinction is less pronounced, the six days of operations may be separated into two groups as well. As before, group a, in black, refers to the group of highest fuel efficiency. The main difference between the two groups comes from the proportion of flights that flew a very efficient approach (i.e.: a very late deceleration). In particular, group a had 50 to 60 % of its flights spending less than 2.5 minutes below 180 kts, whereas for group b only 20 to 30 % of the flights reached that efficiency.

Figure 3-12b presents the cumulative distribution of the minimum separation distances at Atlanta. Apart from Fri 2/22, all days present a very similar distribution. It is believed that severe weather conditions which generated significant delays on that day were the main reason for the overall higher separation distances on that day; in fact, as illustrated on Figure 3-12c, the airport reported that only 29 % of the arrivals were on time during that day. ATC and/or pilots probably increased the separation distances that day because of the weather.



	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Fri - 2/22	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I
Sun - 4/6	CAT-III	CAT-III	CAT-III	CAT-III	CAT-I	CAT-I	IMC	IMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC
Thu - 6/26	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Thu - 7/10	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	VMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC
Sun - 7/13	VMC	VMC	VMC	VMC	CAT-II	IMC	IMC	IMC	VMC	IMC	IMC	VMC	VMC	IMC	CAT-I	CAT-I	VMC
Mon - 8/25	CAT-I	CAT-I	CAT-I	IMC	IMC	IMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	CAT-I	IMC

Figure 3-13: Meteorological Conditions at ATL

The meteorological conditions at the airport during the busiest hours (between 6:00 to 22:00, including about 95 % of all arrivals) are presented in Figure 3-13. Similarly to Los Angeles, the most fuel-efficient days have been shaded in blue for easier visualization. Again, there seems to be a correlation between visual meteorological conditions and higher fuel burn efficiency. The correlation is not as clear as it was at LAX, but the separation of the days of data into two groups was not as straightforward either. For instance, Thu 7/10 has been categorized in the lower fuel efficiency group whereas its fuel efficiency is somewhere in between the most and least fuel-efficient days (see Figure 3-12a); this correlates rather well with the weather conditions oscillating between IMC and VMC that day. In addition, Fri 2/22 and Thu 6/26 are respectively the worst and best days in terms of airport meteorological conditions; these days were also almost the worst and best respectively in terms of fuel burn efficiency. As a consequence, the airport meteorological conditions were judged the most important factor in explaining the differences in fuel efficiency for the days of data available at ATL.

3.3.4 New York City Metroplex

Although the final arrivals to each airport in New York City metroplex are handled by each airport separately, all arrivals have been previously organized by a unique structure, namely the New York Terminal Radar Approach Control (TRACON). As a consequence, the operations to the three airports are coordinated to ensure proper separations while maximizing the overall metroplex capacity. In fact, the combined number of operations for the three airports slightly exceeds that of Atlanta for the five days of operations[4].

Figure 3-14a shows that the distributions of time spent below 180 kts are quite spread (even more than Los Angeles or Atlanta) and could be segregated into 3 groups; Mon 6/23 and Wed 7/23 being the most efficient, Wed 3/19 and Mon 3/31 the least efficient, and Tue 2/5 lying in between. In particular, 20 % of the flights of group c spent more than 10 minutes below 180 kts. Practically, this means that these aircraft entered the 30 nm range of this study close to or below that speed (since it takes 10 minutes to cover 30 nm

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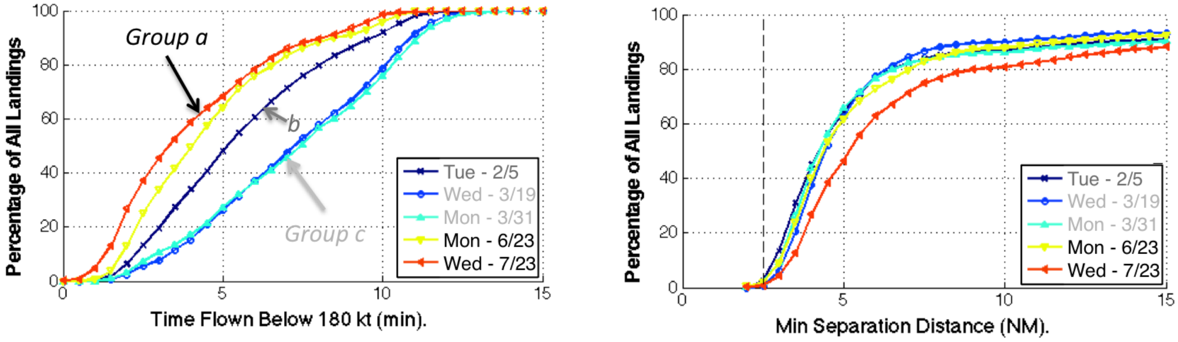
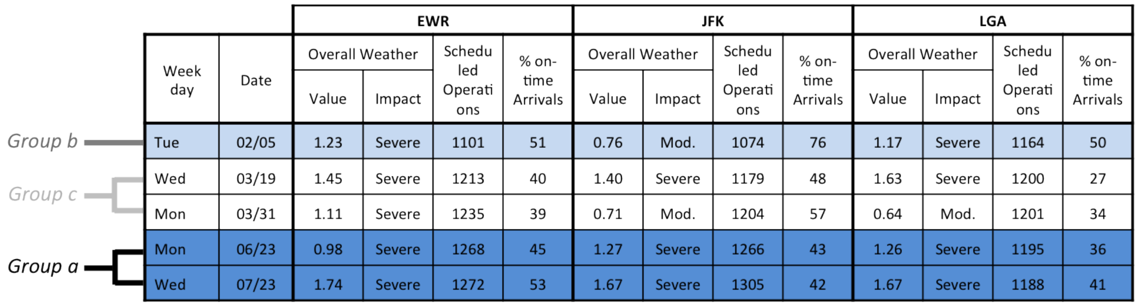
[4] Unlike Los Angeles, Atlanta and Washington DC area, only five days of data were available for the New York airports.



(a) Distribution of Time Flown Below 180 kts (b) Distribution of Minimum Separation Distance



			EWR				JFK				LGA			
	Week day	Date	Overall Weather		Scheduled Operations	% on-time Arrivals	Overall Weather		Scheduled Operations	% on-time Arrivals	Overall Weather		Scheduled Operations	% on-time Arrivals
			Value	Impact			Value	Impact			Value	Impact		
Group b	Tue	02/05	1.23	Severe	1101	51	0.76	Mod.	1074	76	1.17	Severe	1164	50
Group c	Wed	03/19	1.45	Severe	1213	40	1.40	Severe	1179	48	1.63	Severe	1200	27
	Mon	03/31	1.11	Severe	1235	39	0.71	Mod.	1204	57	0.64	Mod.	1201	34
Group a	Mon	06/23	0.98	Severe	1268	45	1.27	Severe	1266	43	1.26	Severe	1195	36
	Wed	07/23	1.74	Severe	1272	53	1.67	Severe	1305	42	1.67	Severe	1188	41

(c) Overall Weather

Figure 3-14: Overall Performance at New York City Area

at 180 kts). Examples of such airspeed schedules are given in the section 3.4.2 (see Figure3-25) and potential reasons are discussed there.

The distributions of separation distances presented in Figure 3-14b are alike, apart from Wednesday 7/23 with overall higher separation distances. Figure 3-14c — for which the shading is related to fuel efficiency — indicates that the weather had especially strong impacts on the airports on that day, although the other days were also quite affected (high overall weather value).

More information on the individual performance of each airport is provided on Figure 3-15. The left column presents the cumulative distributions of time flown below 180 kts, while the right column presents the distributions of separation distances. From the left column, it appears that the grouping of the days in terms of fuel efficiency are quite consistent across the three airports: group a always being the most efficient, group c being the least efficient, and group b lying in between. However, the variations in fuel efficiency are much more pronounced at La Guardia than at Newark and Kennedy. This suggests that there has been a global effect on efficiency in the TRACON — probably coming from weather —, but at the same time not all airports were affected in the same way.

The right column shows that on average, Kennedy airport has higher separation distances than Newark and La Guardia; in particular, 60% of the flights had less than 5 nm of separation at Kennedy whereas for Newark and La Guardia more than 80% of the flights were in that situation, with the exception of Wednesday 7/23. These plots also show that the airports were affected differently by the weather. Wednesday 7/23

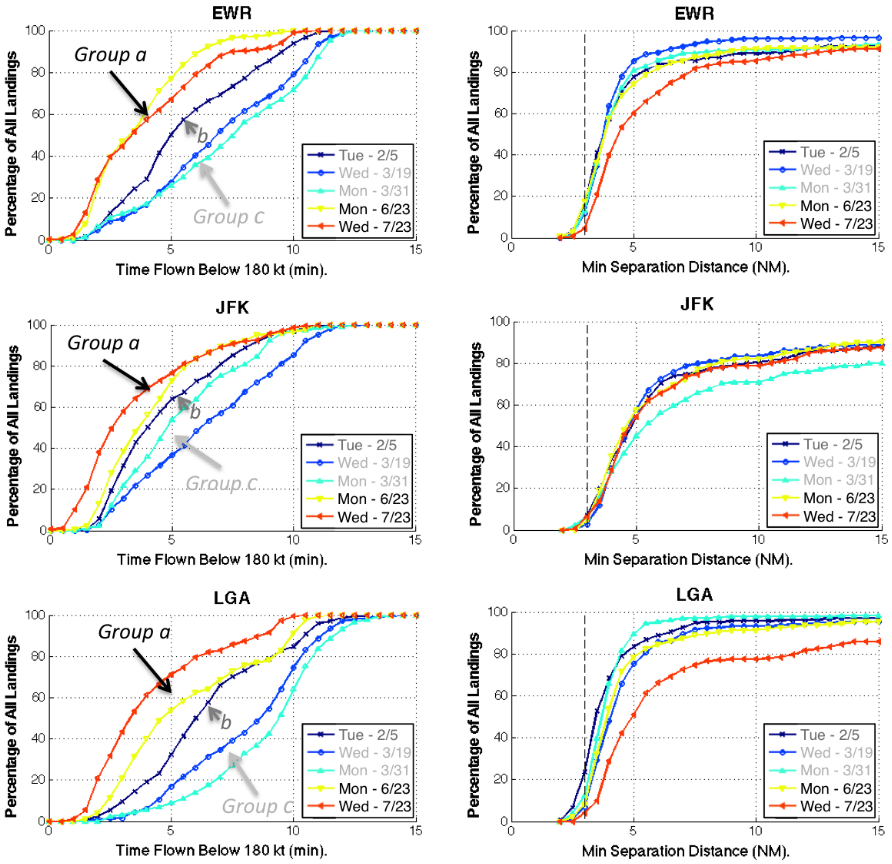


Figure 3-15: Overall Performance at New York City Metroplex by Airport

is very similar to most of the other days at Kennedy, while Monday 3/31 would be the day with highest separations. On the other hand, for Newark and La Guardia, Wed 7/23 had higher separation distances than the other days.

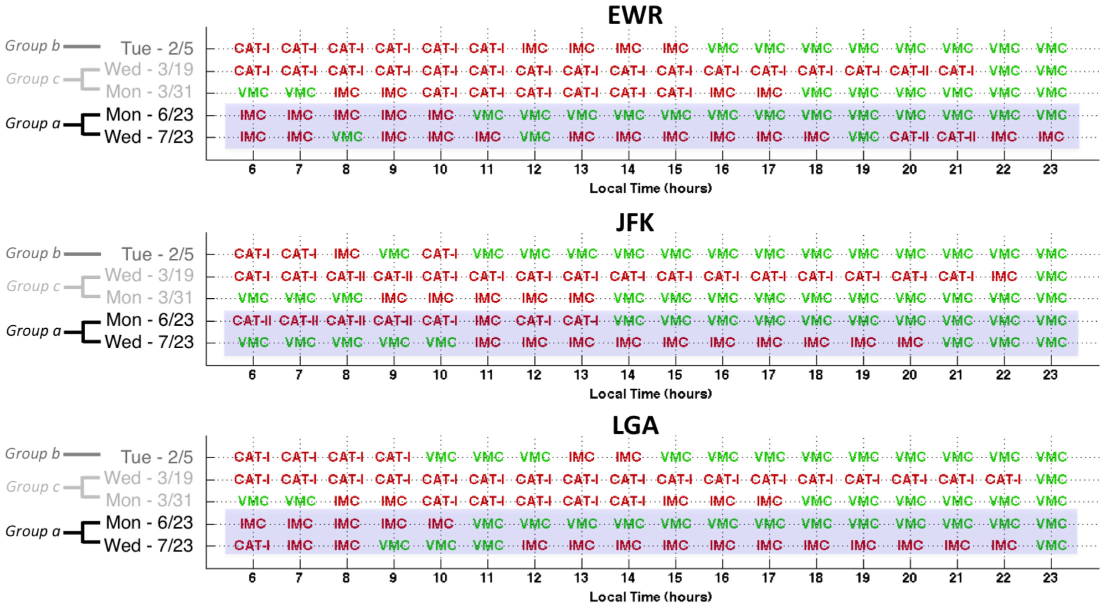


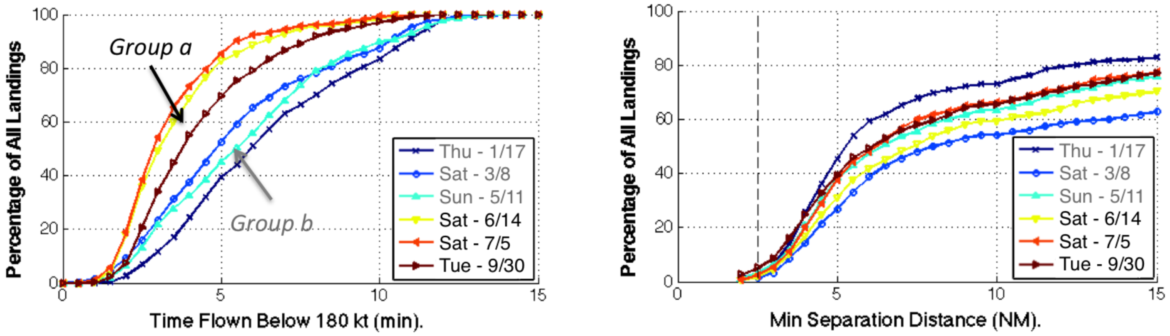
Figure 3-16: Meteorological Conditions at New York Airports

Figure 3-16 presents the meteorological information broken down by airport for the New York City Metroplex. The two most fuel efficient days have been shaded in blue for easier identification. The correlation of performance with weather seems less clear than with Los Angeles and Atlanta. Although some trends exist — Wed 3/19 was an inefficient day and had CAT-I conditions almost all day at the three locations; and conversely, Mon 6/23 was a fuel efficient day with visual conditions during most of the day — the global picture is not very clear. There seems to have been other factors influencing the fuel efficiency than local airport weather at New York metroplex. Since the distributions of time flown below 180 kts were seen to be consistent between the three airports (see Figure 3-14a), it is conjectured that some local weather effects around the airports affecting the availability of the New York airspace could explain variations in the fuel efficiency in the metroplex. In fact, when local weather effects are seen around a stand-alone airport such as Atlanta, the flights can quite easily be re-routed to avoid the weather. This may not be so trivial in New York metroplex given the already intricate air corridors to separate the departures and arrivals of all airports.

In conclusion, the airport weather effect does not seem to explain the fuel burn efficiency in the New York area as well as with Los Angeles and Atlanta, based on the available data. Further work to better understand what caused a lower fuel efficiency could include a study of how weather impacted the available routes to and from the different airports.

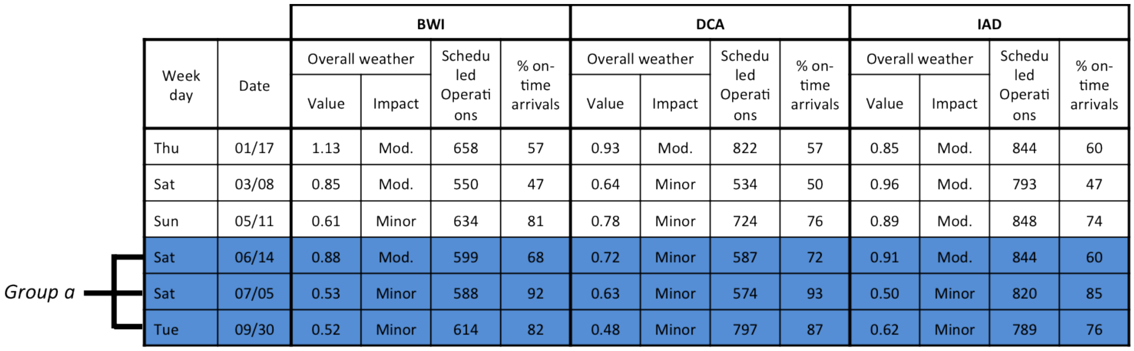
3.3.5 Washington DC Metroplex

Washington DC metroplex is significantly less dense than New York City metroplex, a combination of the fact that traffic volumes are lower and distances between airports are bigger.



(a) Distribution of Time Flown Below 180 kts

(b) Distribution of Minimum Separation Distance



		BWI				DCA				IAD			
Week day	Date	Overall weather		Scheduled Operations	% on-time arrivals	Overall weather		Scheduled Operations	% on-time arrivals	Overall weather		Scheduled Operations	% on-time arrivals
		Value	Impact			Value	Impact			Value	Impact		
Thu	01/17	1.13	Mod.	658	57	0.93	Mod.	822	57	0.85	Mod.	844	60
Sat	03/08	0.85	Mod.	550	47	0.64	Minor	534	50	0.96	Mod.	793	47
Sun	05/11	0.61	Minor	634	81	0.78	Minor	724	76	0.89	Mod.	848	74
Sat	06/14	0.88	Mod.	599	68	0.72	Minor	587	72	0.91	Mod.	844	60
Sat	07/05	0.53	Minor	588	92	0.63	Minor	574	93	0.50	Minor	820	85
Tue	09/30	0.52	Minor	614	82	0.48	Minor	797	87	0.62	Minor	789	76

(c) Overall Weather

Figure 3-17: Overall Performance at Washington DC Area

In terms of fuel efficiency, Figure 3-17a presents a high variability between the six days of data. Sat 7/5, Sat 6/14 and Tue 9/30 are quite efficient, while Thu 1/17, Sun 5/11 and Sat 3/8 are rather inefficient, including having more than 10% of their flights flying more than 10 minutes below 180 kts.

Figure 3-17b shows that the distributions of separation distances are slightly spread apart, but more importantly they represent much higher separation distances on average that observed at the other three locations (Los Angeles, Atlanta and New York City). As noted earlier, for all days at least 20% of the flights benefited from a clear approach, with no aircraft closer than 15 nm ahead. If air traffic congestion is one of the main obstacle to DDAs, then opportunities for greater use of DDAs may be present at Washington metroplex airports due to lower traffic constrains there. Figure 3-17c indicates that each airport has between 500 and 800 operations per day. Most of the days for Washington DC happened to be week-end days, with only two week days (Thursday and Tuesday); however the difference in number of operations for the week days is only significant at Reagan (DCA). The table also shows minor to moderate weather effects for the days of data.

The individual performances of each airport are plotted in Figure 3-18. In terms of time flown with flaps

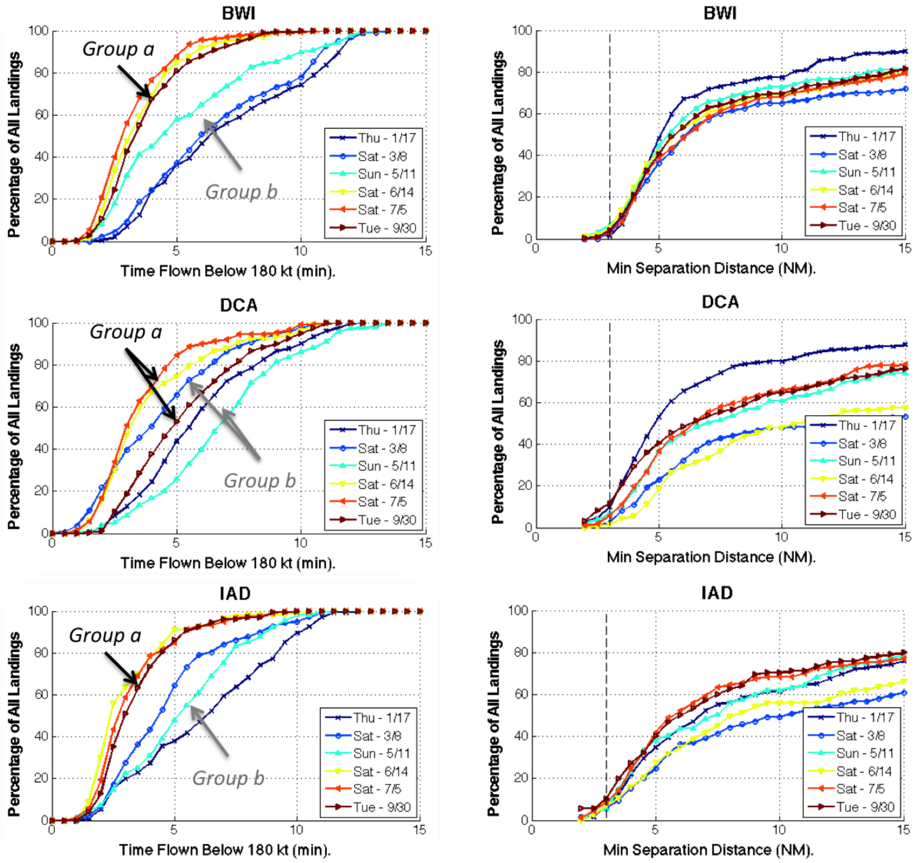
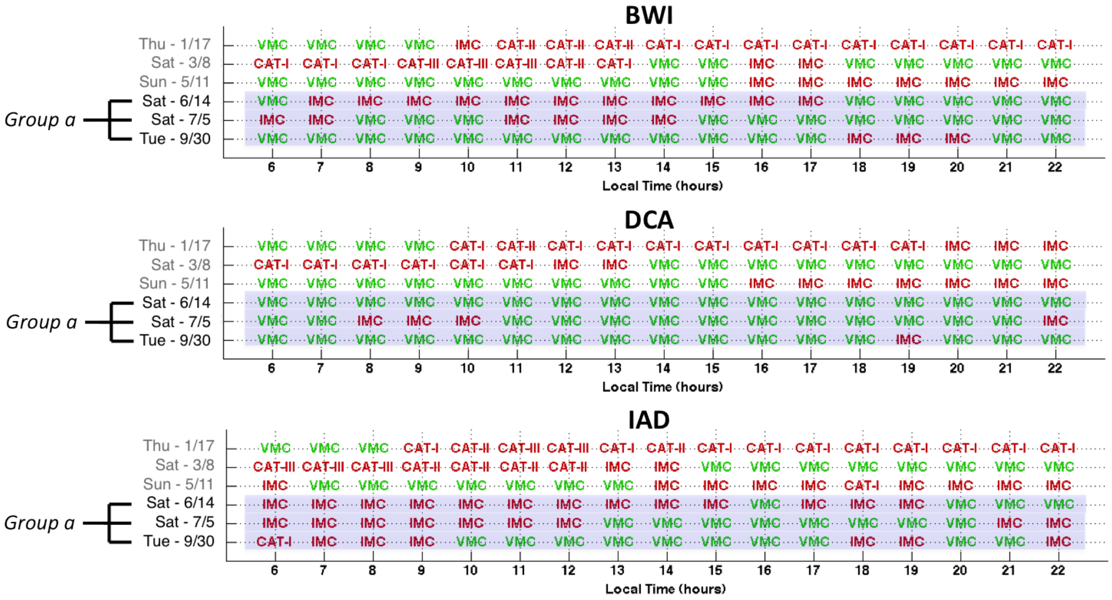


Figure 3-18: Overall Performance at Washington DC Metroplex by Airport

extended (left column), the three airports seem to behave in a similar way. Groups a and b consistently have a high and low efficiency respectively, and except a swap of one day at Reagan (DCA) the ordering of the days in terms of fuel efficiency are the same. The variability in fuel efficiency seems to be higher at Baltimore (BWI) and Dulles (IAD) than at Reagan.

In terms of separation distances (right column), high variations are observed at Reagan while all days are very similar at Baltimore. Dulles stands in between these two behaviors. The variations at Reagan may be partly explained by the higher number of operations during the week days, especially for Thursday 1/17. For Baltimore, the similarity between the curves may reflect a common practice in the sequencing of the aircraft.



BWI

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Thu - 1/17	VMC	VMC	VMC	VMC	IMC	CAT-II	CAT-II	CAT-II	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I
Sat - 3/8	CAT-I	CAT-I	CAT-I	CAT-III	CAT-III	CAT-III	CAT-II	CAT-I	VMC	VMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC
Sun - 5/11	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC
Sat - 6/14	VMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC
Sat - 7/5	IMC	IMC	VMC	VMC	VMC	IMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Tue - 9/30	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	IMC	VMC	VMC

DCA

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Thu - 1/17	VMC	VMC	VMC	VMC	CAT-I	CAT-II	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	IMC	IMC	IMC
Sat - 3/8	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Sun - 5/11	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC
Sat - 6/14	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Sat - 7/5	VMC	VMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC
Tue - 9/30	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	VMC	VMC	VMC

IAD

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Thu - 1/17	VMC	VMC	VMC	CAT-I	CAT-II	CAT-III	CAT-III	CAT-I	CAT-II	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I	CAT-I
Sat - 3/8	CAT-III	CAT-III	CAT-III	CAT-II	CAT-II	CAT-II	CAT-II	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC
Sun - 5/11	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	IMC	IMC	CAT-I	IMC	IMC	IMC	IMC
Sat - 6/14	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	IMC	VMC	IMC	IMC	IMC	VMC	VMC	VMC
Sat - 7/5	IMC	IMC	IMC	IMC	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC
Tue - 9/30	CAT-I	IMC	IMC	IMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	VMC	IMC	IMC	VMC	VMC	IMC

Figure 3-19: Meteorological Conditions at Washington DC

Figure 3-19 presents the meteorological conditions at the three airports. The three most efficient days have been shaded in blue. Similarly to New York, there is no strong correlation of weather with the most fuel-efficient days. Although Thu 1/17 and Sat 3/8 had pretty low conditions during most of the day, some of the most fuel efficient days also had extended period of time with IMC.

3.3.6 Airline Effect

In order to explore if there were effects from differences in training and/or procedures between airlines as to when the deceleration occurs in approach, the data has been segregated by airline for the eight airports. Figure 3-20 shows the number of arrivals per airline with all the days of data at each location grouped together; the airlines having more than 10% of the traffic at each airport were selected for the plot of the fuel burn efficiency as shown in Figure 3-21. All other airlines have been grouped together under “others” and the aggregation of all the flights is represented in black under “all”; this latter line is the same as was shown in the overall assessment of fuel efficiency in Figure 3-7.

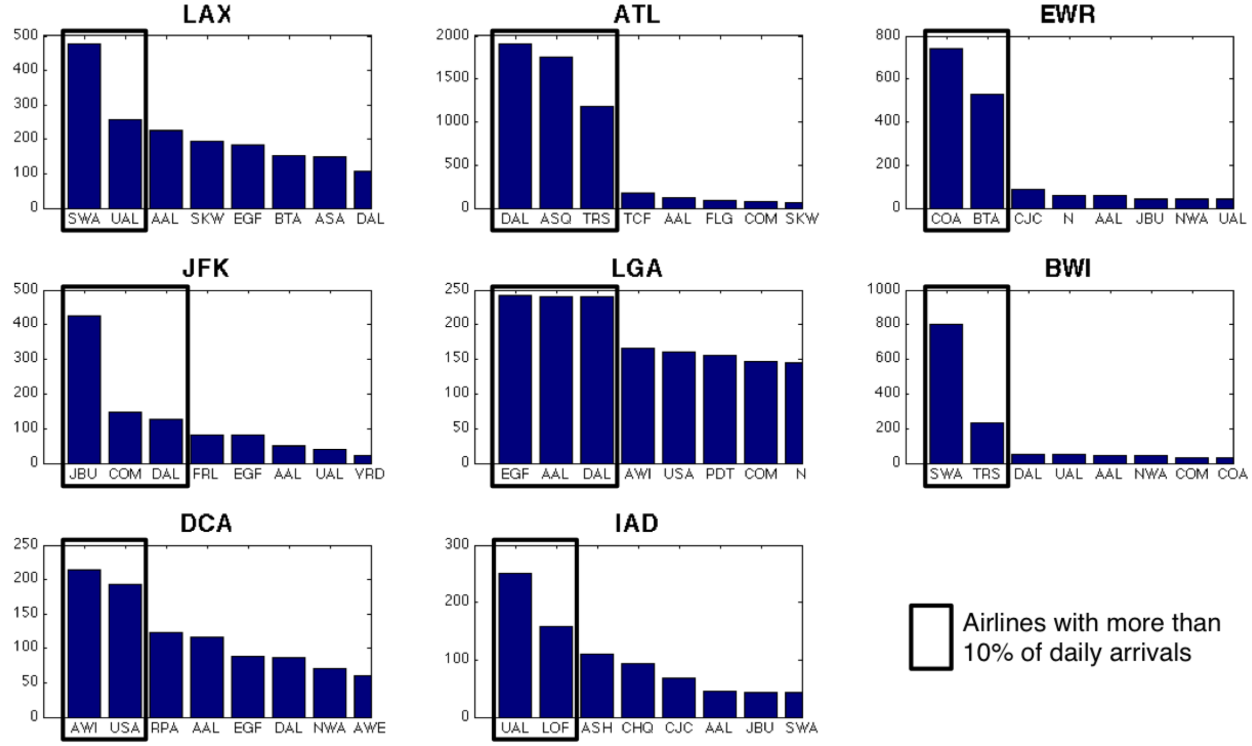


Figure 3-20: Number of Arrivals Broken Down by Major Airlines

Figure 3-21 shows that there is very little variation between the main airlines as to the duration of the descent with flaps extended. This suggests that either ATC had a major role in dictating the airspeed during descent, or that all airlines follow similar guidelines in terms of deceleration; or a combination of both. Although it could be argued that aggregating all days of data may have hidden some of the effects (as high variabilities in fuel burn efficiency from one day to another have been experienced throughout this analysis), the fact that all airlines follow very similar trends for all locations make the possibility of differences from different days canceling each other out very unlikely. In addition, generating this plot for each day would not enable fair comparisons of the distributions either since there would be too few flights.

3.4 Specific Operations with Fuel Burn Reduction Potential

This section reports observations about the potential to increase the implementation of DDAs and their limitations in the context of busy airports. The first case illustrates the effects of different sequencing techniques on the fuel burn efficiency at Atlanta; the second is a more detailed study about limitations of DDAs at La Guardia due to runway configuration; and the last case shows an occurrence of primary DDA

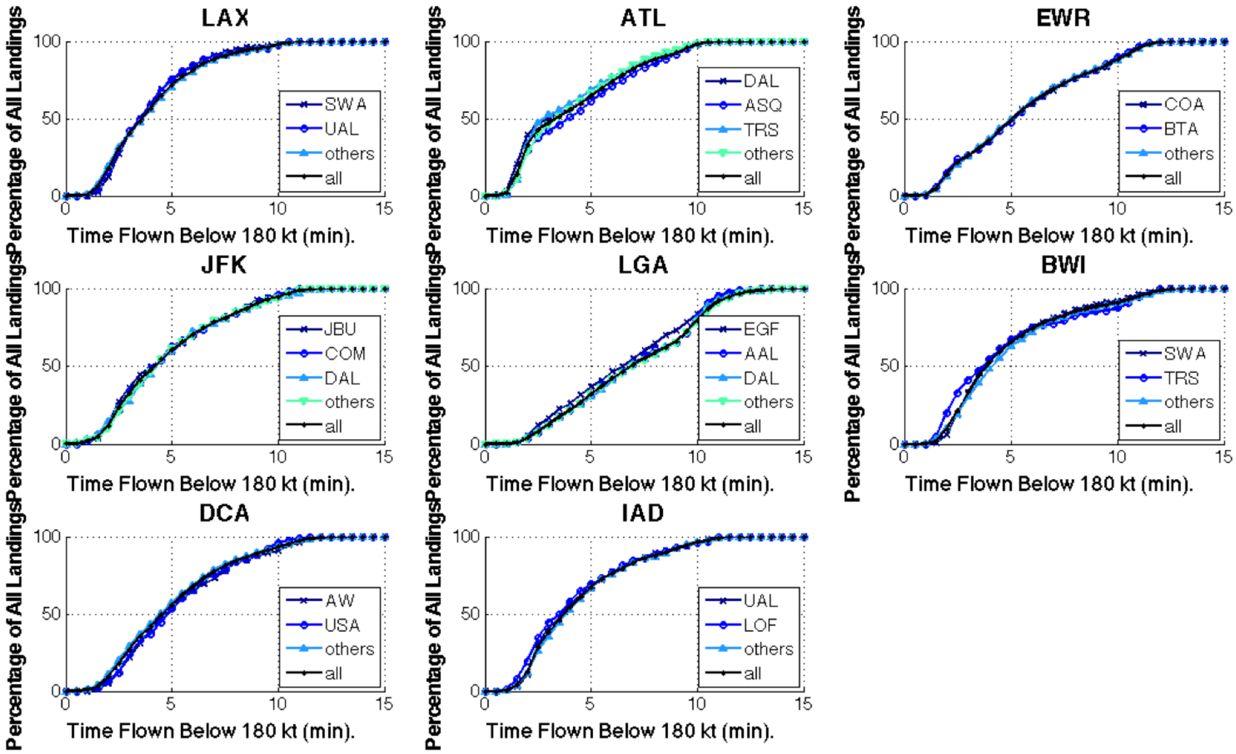


Figure 3-21: Time Flown with Flaps Extended Broken by Major Airline

potential opportunity arising from the opening of a second runway for arrivals at Newark, along with its limitations.

3.4.1 Controller Technique

In some cases, variations of fuel burn efficiency over relatively short periods of time have been observed; these might indicate differences in controller technique.

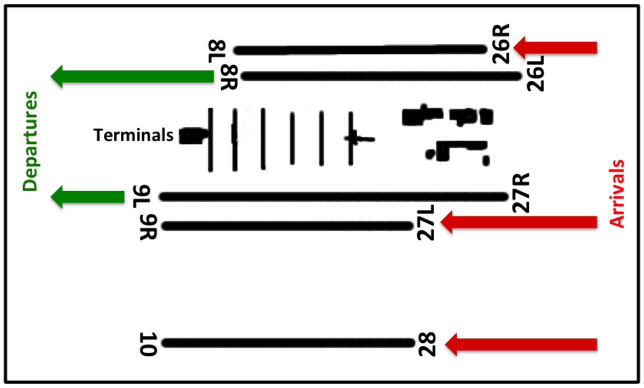


Figure 3-22: Runway Configuration at Atlanta

Figure 3-22 shows the runway configuration at Atlanta for June 26th 2008 between 19:00 and 22:00 local time. Amongst the three runways dedicated to arrivals, the two busiest - 27L and 26R - are presented in this study; the throughputs on these two runways were quite similar between the two sample hours of the analysis (34 and 32 landings for 27L versus 33 and 41 landings for 26R respectively). The efficiency plots for the Large and B757 following Large wake-vortex category are presented on the left in Figure 3-23 on an hourly basis. Flights have been shape and color-coded according to the runway on which they landed. In addition, the right part of the graph represents the airspeed distribution of aircraft belonging to this wake-vortex category by runway; the dark patch represents the 25-75th percentiles, while the lighter patch includes the 5-95th percentiles as before. The horizontal dashed line marks the 180 kts speed limit below which flights are assumed to have extended partial flaps.

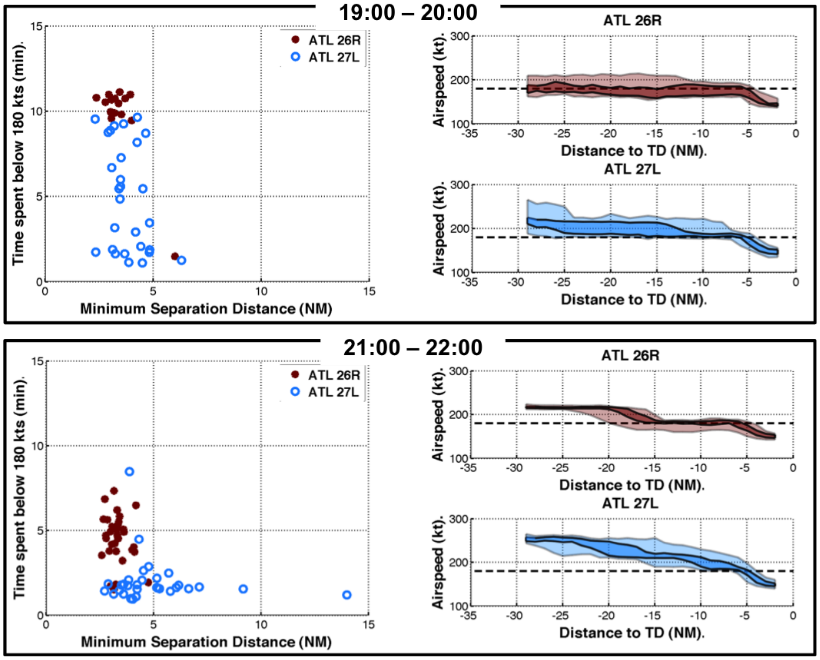


Figure 3-23: Sample ATL DDA Opportunity Analysis (06/26/08, 19:00-20:00 and 21:00-22:00)

By observing runway 26R (brown dots) between 19:00 and 21:00, it appears that flights were clustered in the "inefficient/constrained" part of the efficiency graph (top left region). In addition, the airspeed distributions on the right confirm that flights were mostly conducting the last 30 nm of the descent at constant speed around 180 kts (which is less efficient than ideal in terms of fuel burn) but low inter-aircraft separations were achieved hence resulting in high runway throughput. However, flights on 26R exhibited higher fuel efficiency between 21:00 and 22:00. In fact, flights moved from the initially grouped cluster in the "inefficient/constrained" area (top left region) towards the relatively more efficient (although still constrained) lower left part of the graph. At the same time, the airspeed distribution on that runway exhibits a different shape, with a two-step speed target descent, one at 220 kts and one at 180 kts. This indicates that a more efficient air traffic control technique was in place during this period. It is also interesting to note a similar change for runway 27L. Between 19:00 and 21:00, flights were observed with varying efficiency in the constrained part of the plot on the left, with small aircraft separations. Although flights were more fuel-efficient than runway 26R on average, a larger spread in both fuel and throughput efficiency was observed. This is confirmed by the airspeed distribution profiles, which show that most flights maintained their airspeed higher than 180 kts for a longer period of time (i.e., less time below 180 kts), thus resulting in more fuel-efficient descents while simultaneously achieving short inter-aircraft separations. However, between 21:00 and 22:00 flights were much more tightly grouped in the high fuel efficiency part of the plot (less time below 180 kts) while the airspeed distribution was consistent with the Delayed Deceleration Approached concept, with a faster descent and a later deceleration. In addition, although the throughputs were fairly consistent on that runway over the three hours, a few more aircraft were located in the unconstrained part of the efficiency plot between 21:00 and 22:00 than before. The most likely reason for this is that since all aircraft are flying faster, there is more time between aircraft for the same throughput per hour. This example illustrates the potential for increased DDA in the context of current operations and the potential impact of specific air traffic controller technique.

3.4.2 Predictability

Some circumstances may require very predictable flows and motivate air traffic controllers to slow down all aircraft and standardize airspeed very early. One example at La Guardia is detailed below.

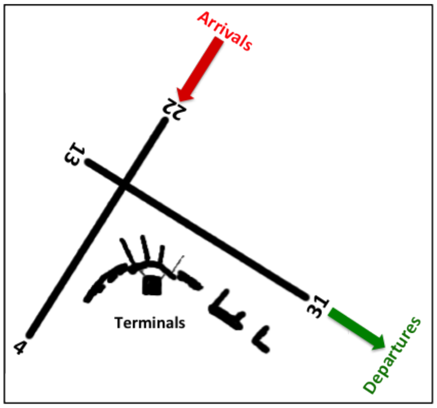


Figure 3-24: Runway Configuration at La Guardia

Figure 3-24presents the runway configuration at La Guardia during the analysis period. More insights on the operations are obtained from Figure 3-25, which presents the hourly efficiencies and airspeed distributions from 12:00 to 15:00 on March 31^{st}, 2008.

Flights are mostly in the “constrained/inefficient” (top left) region of the graph. At the same time, the darker areas of the airspeed profiles (representing the 25th to 75th percentiles of airspeed) are very similar from one hour to another. In addition, the distributions are tightly centered on 180 kts, with a final deceleration consistently starting around 6 nm from touch down indicating a standard air traffic control technique.

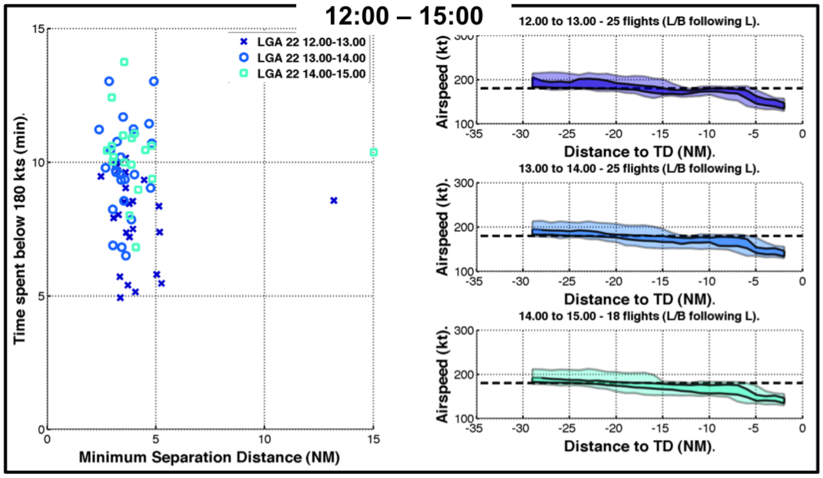


Figure 3-25: Hourly Airspeed Distributions at La Guardia (03/31/2008, between 12:00 and 15:00 hrs local)

A potential explanation comes from the runway arrangement, as presented on Figure 3-24. While arrivals are assigned to runway 22, departures take place on the intersecting runway 13. In order to process the demand in terms of takeoffs and landings at LGA, controllers have to precisely sequence the departures and arrivals. It is possible that controllers assign early speed reductions for the arrivals in some challenging circumstances (volume of traffic, weather, etc.) in order to produce a more predictable arrival flow of aircraft for runway 22 to enable the safe sequencing of departures on the crossing runway between arrivals. It is also possible that slowing all aircraft early is part of a standard procedure used by the TRACON (possibly upon request from the tower controllers at La Guardia) to make flows more easily manageable in periods of high workload for the controllers.

This case presents an interesting opportunity for DDAs. If controllers could be guaranteed a similar predictability in the flow with faster airspeeds and later decelerations below flap extension speeds, they would probably allow faster flows which at the same time enable stable or increased throughputs. Decision support tools may be useful in helping controllers manage these faster flows without increase in workload.

3.4.3 Runway Interactions

Figure 3-26 presents an expanded view on the runway configuration at Newark on March 31st 2008. Departures were conducted on runway 22R while arrivals were primarily on runway 22L with some arrivals on runway 11 during periods of high demand. Figure 3-27 shows the efficiency plot between 20:00 and 21:00 hours local time when runway 11 was in use for the second consecutive hour. Only 8 aircraft landed on this runway, all of them belonging to the Large wake-vortex category. These are notably on the right of the efficiency plot, which means that they all had high separation distances with the preceding aircraft. However, they did not perform well in terms of fuel burn efficiency, as most of them were in the top right region. A possible explanation for this could come from runway interactions. Due to the intersection of the runways,

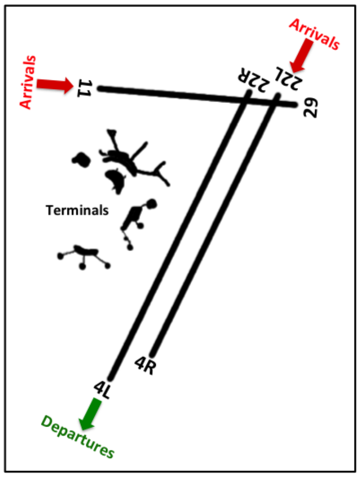


Figure 3-26: Runway Configuration at Newark

departures on 22R cannot be operated independently from the arrivals on runway 11. As a consequence, although arrivals on runway 11 were not constrained by the separation with the preceding aircraft to that runway, they were most likely affected by the departures being processed on runway 22R. The other arrivals on runway 22L must also have impacted the availability of runway 11. Therefore, the lower than expected fuel efficiency observed in Figure 3-27 may be explained by the constraints from operating the intersecting runways; in addition, the arrivals on 11 had to fly another geographic route than the main flow on runway 22L. Since only eight aircraft landed during that hour on runway 11, it is possible that they were routed individually through the airspace. This may have added additional constraints to the airspeed they could fly, or perhaps ATC slowed them down early to ease the handling of this different routing.

This is another case where decision support tools may allow increased usage of DDAs by helping controllers manage faster flows of aircraft on intersecting runways.

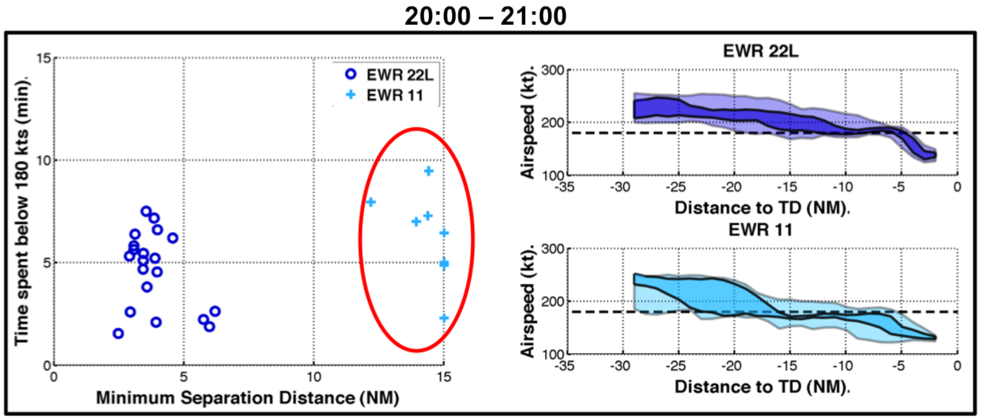


Figure 3-27: Sample Newark DDA Opportunity (03/31/2008, 20:00 to 21:00 hrs local)

3.5 Conclusions

Radar data from eight different airports and six different days (only 5 for New York metroplex airports) has evidenced large differences in fuel efficiency between days and between locations. The variations between days have seemed to correlate with the airport meteorological conditions for Los Angeles and Atlanta. The fact that these variations were not reflected on separation distances with preceding aircraft suggests that variation in airspeed schedule were primarily driven by pilot behavior.

For the two metroplexes studied — New York and Washington DC — the correlation with destination airport meteorological conditions was much weaker. It is believed that local weather effects around airports in the metroplex have also played a role by globally affecting the flows to and from the airports, although additional radar and weather data would be necessary to verify this hypothesis.

From the available data, there was no evidence of specific differences in operating procedures between the main airlines at all the locations.

In addition, some specific behaviors resulting in low fuel efficiency have been identified in an hourly exploration of the data. The reasons for low fuel efficiency in these cases were believed to be controller technique, need for predictability with high workload situation and management of runway interactions. Exploration of bigger sets of data would enable to evaluate the frequency of occurrence of such behaviors.

Chapter 4

Conclusions and Future Work

4.1 Conclusions

Simple changes in operational procedures such as favoring later decelerations while on approach can lead to improvements in fuel burn consumption.

This work has first assessed the correlation between the time at which the deceleration occurred and the fuel burn consumption during approach. DFDR archive data have been used in order to analyze detailed flight information that may have played a role in fuel burn. The study has also been restricted to arrivals on a three degree descent to isolate the effects from altitude changes and focus on the speed profiles.

Important variations in fuel burn during approach have been observed, with a factor of two difference between flights with lowest and highest fuel burn between 10,000 ft and touch down. The flights with lowest fuel burn were observed to have late deceleration and flap extension compared to the average behavior, while the least fuel-efficient flights spent most of the approach at low speed with flaps extended. A correlation analysis has confirmed that fuel burn most strongly correlated with airspeed and time spent with flaps extended compared to other procedural variables.

An estimation of the fuel burn reduction that could be achieved if aircraft that decelerated early flew instead as the most efficient flights has been presented. This reduction potential has been extrapolated to the nation-wide fleet of aircraft resulting in a promising benefits pool for DDAs.

The second part of the study has analyzed potential barriers to implementation for DDAs. Discussions with airlines and air traffic controllers have highlighted some issues that may have motivated early decelerations. These were separated into issues happening at the aircraft level, which were mostly the decision of the pilot; and those that happened at the air traffic level, principally managed by air traffic control. This second group of potential barriers to implementation, believed to have the greater effect on DDAs, has been analyzed further by observing PDARS data from airport in four locations: Los Angeles, Atlanta, New-York City (Newark, Kennedy and La Guardia) and Washington DC (Baltimore, Reagan and Dulles). The data has been filtered down to one given wake-vortex class — Large + B757 following Large — in order to have similar separation distance requirement and aircraft speed capabilities for comparison. This wake class was chosen as it encompasses the great majority of the flights at the airports considered. Since the PDARS data does not include internal information about the flights, surrogate metrics for fuel burn and air traffic constraints have been developed. In particular, the fuel burn efficiency has been assessed from the time flown below first flap extension speed, given the high correlation observed in the first part of this study.

Analysis of the data showed that meteorological conditions around and at the destination airport had some effect on the fuel-efficiency. In particular, instrument weather conditions have been shown to affect the speed schedule of the flights more than the separation distance between flights. This suggests that the earlier decelerations observed in instrument conditions were a decision of the pilots, most likely as part of their instrument arrival procedures. Also, the different airports were affected differently by weather conditions, in particular within a given metroplex. La Guardia, for instance, happened to have more variability in fuel efficiency than Newark or Kennedy. This suggests that the organization of the airspace in the New York metroplex introduces some speed restrictions for La Guardia in some circumstances. However, for all airports airlines seemed to have behaved very similarly in terms of speed schedule; that suggests there are no major difference in their operating practices as to deceleration in approach.

In addition, some specific behaviors have been identified by studying the data in detail by hour of operation. Operations with consistent low fuel efficiencies have been observed and are believed to be the consequence of a deliberate decision by ATC to slow aircraft down. The motivations behind this are believed to be related to the management of airspace and/or controller technique. From the observations that were made, the early speed target of 180 kts at La Guardia had the most repeat occurrences in the data. It is believed that the very dense airspace and the demand consistently close to capacity at that airport motivated the usage of this practice.

4.2 Future Work

The current work has developed a methodology to assess opportunities for DDAs and identify potential barriers to implementation. A small set of data as been used to apply the methodology and capture some of the barriers to DDAs. However, more radar data would be necessary in order to find statistically significant correlations between presumed factors and early decelerations. Some directions of study to get more insights on the reasons behind early decelerations are described next.

Extend Time Periods Studied at Airports

Valuable insights would most likely be gained by applying this methodology to an extended period of data (e.g.: a month) at a given location. This would not only enable to observe trends related to specific modes of operation at that location, but it would also enable to explore the impacts of weather and other aperiodic factors on the fuel efficiency in greater depth. Additional weather data around the airports would also be valuable to understand the impacts of weather effects on metroplexes in particular. Since these are believed to play a major role on the potential for DDA, such a study would contribute to the overall assessment by helping refine which weather components are most directly correlated with early deceleration, and thus enable extrapolations of occurences of early deceleration by using weather historical data.

Extend Study to Other Wake-Vortex Classes

Limiting the study to one wake-vortex category (Large and B757 following Large) has facilitated the assessment of opportunities for DDAs by having a common reference for separation distance and airspeed capabilities. However, the DDA fuel burn saving potential for Heavy and Super-Heavy may be even bigger than for Large (even in relative terms) given that most of these aircraft start extending flaps at higher airspeed, thus spending even more time with flaps extended. Therefore, even though they represent a lower proportion of aircraft, it would be worth expanding the analysis to these aircraft categories.

Analyze Air Traffic Control Commands

Another valuable input would be to analyze recording of air traffic controller commands and map them to observations made from the radar data. This would enable to identify relationships between the observed decelerations and either ATC commands or decisions from the pilots, thus providing more insight into which stakeholder decided to decelerate early. In addition, this could help understand standard practices at given locations and their potential effect on early decelerations.

Appendices

Correlation Matrices from DFDR Data

The analysis of the correlation matrices in Section 2.3 had shown that total energy negatively correlated with spoiler usage for the A320 (i.e. the more total energy, the less spoiler usage). This was unexpected as spoilers were assumed to be used as a means to dissipate excess of energy during descent. This section investigates this correlation further.

The main factors responsible for differences in energy between flights at the beginning of this study are the mass, varying within a given aircraft type due to different payloads; the initial airspeed (when crossing the 31.4 nm cut-off for the scope of this study); and the initial altitude, due to the tolerances around the three degree descent profile introducing $\pm 1,000$ ft variations, as detailed in Equation 2.1. Therefore, further insights on the correlation of total energy with spoiler were gained by looking for separate correlation with mass, initial airspeed and initial altitude. The extended correlation matrices are shown in Figure 4-1.

The new correlations lines (13 to 15) present obvious correlations (for instance that of airspeed with initial airspeed, or total energy with mass, initial altitude and initial airspeed) but also enables to investigate further the correlation of total energy with spoiler usage for the A320. This figure shows that in fact, this correlation comes from initial altitude correlating negatively with spoiler usage (i.e.: the higher the initial altitude, the lower the spoiler usage). Although it is surprising, it is possible that it comes from standard techniques of spoilers usage with A320 during approach. Discussions with pilots (and potentially analysis of more DFDR data to verify if this was an artifact from the data set) would be necessary to further investigate that hypothesis.

Correlation of Fuel Burn with Different Degrees of Flap Extension

The correlation of fuel burn and flap extension have been further explored in Figure 4-2. This figure shows that the strongest correlations are that of the first flap extension for the A320 and the B757. Latter flap extension correlates better with fuel burn for the B777, which is consistent with the fact that this bigger aircraft has to extend some light amount of flaps earlier in descent (at higher airspeed speed). For this aircraft size, the next degrees of flap extension seem to be much more significant (more data would be necessary to

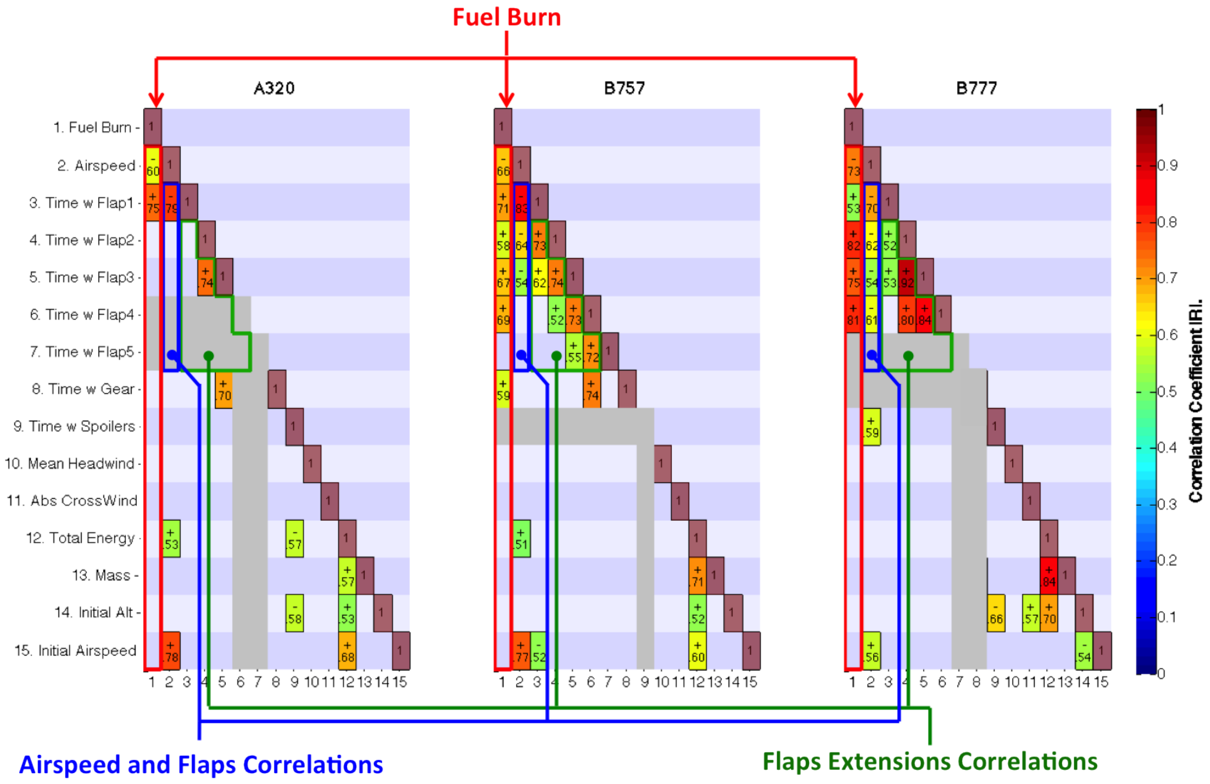


Figure 4-1: Correlation Matrices Showing only $R^2 > 0.25$ ($|R| > 0.5$)

properly conclude on that point).

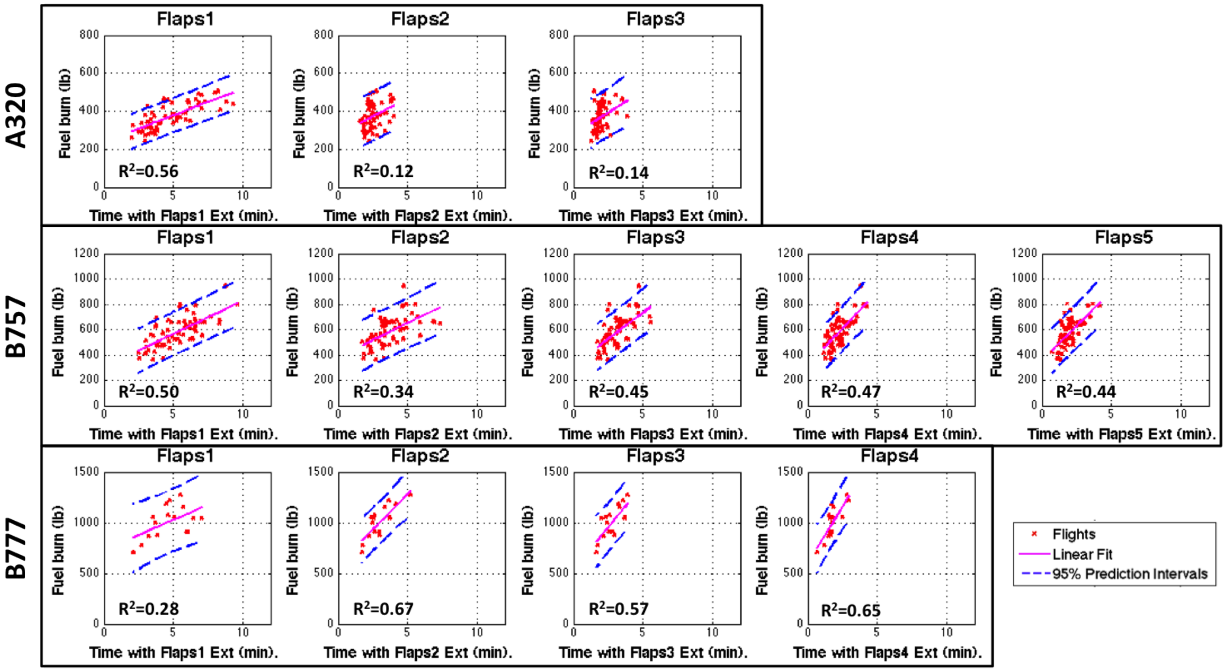


Figure 4-2: Correlation of Fuel Burn with the different Flap Extensions

Efficiency Plot

The potential DDA opportunity for each flight was assessed by combining the time spent below the first flap extension speed and the minimum separation distance with the preceding aircraft, as represented in Figure 4-3. For the purpose of illustration, the fuzzy blue lines define frontiers between notional "efficient" and "inefficient" regions in terms of time spent below the first flap extension airspeed of 180 kts, and "constrained" and "unconstrained" regions in terms of separation distance with the preceding flight, thus defining four quadrants. The frontier lines are fuzzy to represent that these are notional boundaries between the different quadrants. Note that, in this axis space, the further to the left of the horizontal axis the greater the throughput efficiency (from tighter aircraft separations), and the nearer to the bottom of the vertical axis the greater the fuel efficiency (from less time below the flaps extension speed). Therefore, the ideal operating point is at the bottom left. Such plots enable the operational fuel burn reduction potential for DDA to be assessed for a given traffic flow situation.

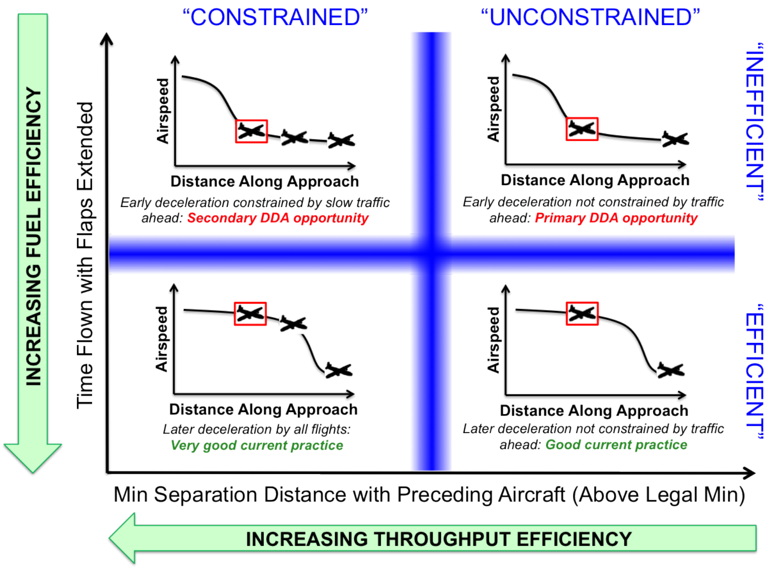


Figure 4-3: Illustration of DDA Opportunity Analysis

The bottom right quadrant shows unconstrained and efficient flights, which represents good current practice of aircraft flying DDA speed profiles during low demand periods. The bottom left quadrant also presents efficient flights, although these were also constrained in terms of spacing as would typically be seen at high demand times, illustrating that efficient speed profiles are not precluded at peak times if the entire stream can operate with Delayed Deceleration. Operations within this quadrant are an example of very good current practice. The top left quadrant, on the other hand, depicts inefficient constrained flights. These embody lower speed flows of aircraft, possibly due to slower aircraft upfront forcing following flights to also slow down early or air traffic control strategies which slow down the stream of aircraft for better control. There is a potential for increased DDA use for flights within this region, but because of the constrained traffic flows, this is more complex proposition than for the top right quadrant which contains unconstrained and inefficient flights (i.e. these had enough separation for the trailing aircraft to fly faster, but for some reason spent an extended period of time at low speeds). It is suggested that the best near-term potential to reduce fuel burn by flying more DDAs lies in this latter area, as there is no obvious constraint preventing the flight from operating a DDA profile, although there may be constraints which are not visible in the separation parameter.

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