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Investigating Benefits from Continuous Climb Operating Concepts in the National Airspace System

Data and Simulation Analysis of Operational and Environmental Benefits and Impacts

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***Abstract*— Operational improvements have the potential for near term environmental and energy benefits in the National Airspace System. Research into terminal area operational improvements has predominantly focused on the descent phase of flight and improvements of operational performance using continuous descent approaches, also known as optimized profile descents. This paper primarily focuses on the climb phase of flight and investigates the need for continuous climb operations. The paper presents the results of an analysis which quantifies the prevalence of inefficiencies in the departure phase across the National Airspace System and the magnitude of operational and environmental performance change if continuous climb operations are implemented at certain airports. Results show that climb inefficiencies occur on average for 30% of departures in the National Airspace System. A detailed operational and energy analysis at Boston Logan International Airport, Denver International Airport and Los Angeles International Airport found that the average potential fuel savings from continuous climb operations range between 6 and 19kg per departure, with annual carbon dioxide savings of 6,970 tons, 3,380 tons and 7,360 tons respectively. The distribution in fuel savings is skewed, with a few operations having greater than average fuel savings. Implementing continuous climb operations for 18% of operations could result in the capture of 59% of total fuel savings from continuous climb operations. Each airport has signature concentrations of level-offs at certain altitudes. This provides evidence of the role of airspace design and constraints in climb inefficiencies. Based on results to date, change in noise impact using conventional noise metrics is inconclusive. However, alternative noise metrics showed significant potential noise benefits from continuous climb operations.**

Keywords- departure management; continuous climb operations; environmental benefit; operational improvement

I. Introduction

NextGen is the Federal Aviation Administration (FAA) plan to modernize the National Airspace System (NAS). Through NextGen, the FAA is addressing the impact of air traffic growth by increasing NAS capacity and efficiency, while simultaneously improving safety, reducing environmental impacts, and increasing user access to the NAS. To achieve its NextGen goals, the FAA is implementing new routes and procedures that leverage emerging technologies and aircraft navigation capabilities [1].

Aircraft climb profile optimization is one such procedural change which has the potential to contribute to NextGen goals. Continuous Climb Operations (CCO) is an airspace enhancement allowing for the flight profile to be optimized to the performance of an aircraft, airport and meteorological conditions [2, 3, 4].

Research investigating aircraft terminal operating procedures has tended to focus on arrival procedures. Research into and development of optimal profile descents (OPDs) and delayed deceleration approaches (DDAs) has shown that OPDs have the potential to produce environment and energy benefits by removing inefficiencies during the descent phase of flight [2,3]. OPDs involve removing low altitude level-offs, and conducting a continuous approach at low thrust settings, fuel burn, and noise levels, resulting in significant environmental and energy benefits, which are currently being accrued as procedures are implemented throughout the NAS.

Flight operations during descent phases are generally characterized by low throttle, engines running close to idle settings (i.e. low fuel flows), and low aircraft gross weights, given that most of the fuel on board is burned during the cruise portion of flight. During the climb phase of flight, there could be benefits from the optimization of climb procedures, especially given that engines generally run close to full throttle settings (i.e. high fuel flows) and aircraft climb at higher gross weights. CCO may therefore have the potential to further reduce aircraft fuel burn, climb time, noise, air quality impacts and greenhouse gas emissions.

In addition, CCO has the advantage of leading to reduced flight crew and controller workload though the design of procedures that require less controller intervention.

Since CCO has yet to be implemented by Air Navigation Service Providers (ANSPs), current field experience is limited. Furthermore, limited research has been conducted to date. The French National Institute for Transport and Safety Research (INRETS) has investigated and documented an optimization model for aircraft takeoffs that resulted in noise and fuel consumption reductions. Performances of an optimal and standard takeoff flight were studied and compared. It was found that avoiding sudden changes in aircraft thrusts during takeoff results in lower noise level and lower fuel consumption. The optimal thrust procedure has a parabolic curve compared to that of the standard three level thrust reductions procedure. This study was limited to jet powered aircraft [4].

There has been limited research on improving the climb phase of flight, and the potential benefits of CCOs are less understood [5, 6 and 7]. In order to inform future research, investments and implementation of these concepts, there is a need to assess the operational and environmental benefits of CCO concepts.

CCO in this analysis refers to a departure that has level-offs removed–in other words, an uninterrupted climb. ICAO defines CCO as, "an aircraft operating technique enabled by airspace design, procedure design and facilitation by ATC, enabling the execution of a flight profile optimized to the performance of the aircraft. The optimum vertical profile takes the form of a continuously climbing path."

This analysis assumes that an unimpeded climb based on existing radar data falls within the ICAO definition of CCO, and represents the flight profile optimized to the performance of the aircraft, taking into account operator's value of time, captured by the cost index. In other words, the analysis assumes that even if an operator could conduct a CCO, they may not conduct a fuel optimal departure, because of the value of time. Unimpeded climb with optimal cost index is scoped as a potential next step.

II. APPROACH AND METHODOLOGY

The approach and methodology to quantify the operational and environmental benefits of CCO concepts included the following three steps, illustrated in Fig. 1.

(1) Scoping analysis of NAS-wide inefficiencies in the climb phase of flight, quantifying the number of operations impacted by departure inefficiencies, and understanding geographic, operator, and aircraft type distribution.

(2) In depth analysis of departure inefficiencies at three airports in the NAS, including:

   a. Simulation of radar tracks which may include level-offs and assessment of the energy and operational performance using the FAA's simulation platform, the Aviation Environmental Design Tool (AEDT).

   b. Simulation in AEDT of the energy and operational performance of radar tracks of departures with level-offs removed to replicate potential unimpeded continuous climb operations.

   c. Comparative analysis of CCO sample with baseline operations.

(3) Throughout the analysis, there was an investigation of the cause of level-offs, and identification of opportunities for improved operational and fuel efficiency.

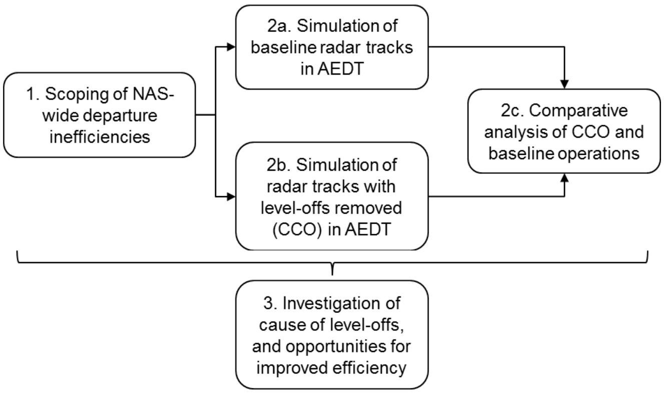

Figure 1. High level approach to quantify the operational and environmental benefits of continuous climb operations.

III. SCOPING ANALYSIS OF INEFFICIENCIES IN THE CLIMB PHASE OF FLIGHT

In step 1, NAS-wide inefficiencies are identified. Climb inefficiencies, or level-offs, are defined as periods in the departure during which the aircraft is below 80% of its top of climb altitude and has a climb rate of less than 1000 feet per minute. Fig. 2 illustrates a sample climb profile where altitude is plotted as a function of time, with level-offs highlighted.

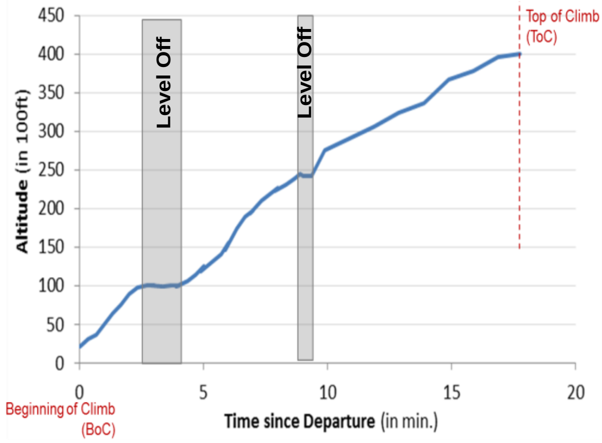

Figure 2. Altitude profile of a sample departure, as a function of time, with level-offs highlighted.

NAS-wide data was used and analyzed for step 1. Operational data was collected for a full week of operations from April 4th to April 10th 2011 from the Enhanced Traffic Management System (ETMS). The ETMS is a data exchange system supporting the management and monitoring of national air traffic flow. ETMS processes all available data sources such as flight plan messages, flight plan amendment messages, and departure and arrival messages. The FAA William J. Hughes Technical Center assembles ETMS flight messages into one record per flight. ETMS is restricted to the subset of flights that fly under Instrument Flight Rules (IFR) and are captured by the FAA's enroute computers. All Visual Flight Rules (VFR) and some non-enroute IFR traffic are excluded. The ETMS actual "as flown" (i.e. position update messages also called "TZ" messages) track data was used as the basis for reconstructing the climb and descent trajectories. In addition, the ETMS flight information files (i.e. “AF” files) that capture flight level information, such as airports of departure and arrival and aircraft type, were used. Both datasets were linked using flight record numbers and time stamps. For this study, the use of a full week of ETMS data allowed for the analysis of approximately 500,000 flights. Operations from wide body jets (WBs), narrow body jets (NBs) and regional jets (RJs) were the main focus of this study.

NAS-wide geographical distributions of level-offs were generated by recording and plotting the latitude and longitude of flight segments affected by level-offs. Fig. 3 shows the results of a geo-spatial analysis of level-offs in the climb phase during the full week of operations from April 4 through April 10 2011. The NAS-wide distribution of inefficiencies in the climb phase of flight occurs around major airports and is concentrated in dense and congested airspace, such as the North East corridor.

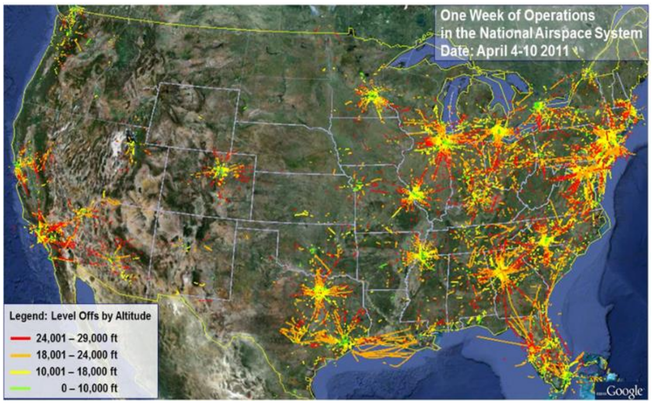

Figure 3. System-wide distribution of level-offs in the climb phase during one week of operations in the continental United States.

Approximately 30% of flights analyzed were affected by at least one level-off. Among the flights that exhibited at least one level-off, approximately five percent of the total climb time (time between BoC and ToC) was spent maintaining constant altitude.

The distribution of level-offs was also categorized by airport origin, as shown in Fig. 4 It was found that level-offs tend to concentrate at the periphery of a few key airports, including Philadelphia International Airport (PHL), Hartsfield-Jackson Atlanta International Airport (ATL), LaGuardia Airport (LGA), Detroit Metropolitan Wayne County Airport (DTW), O'Hare International Airport (ORD), and John F. Kennedy International Airport (JFK) This observation validates the hypothesis that level-offs result from airspace constraints and air traffic management practices in congested/dense airspace.

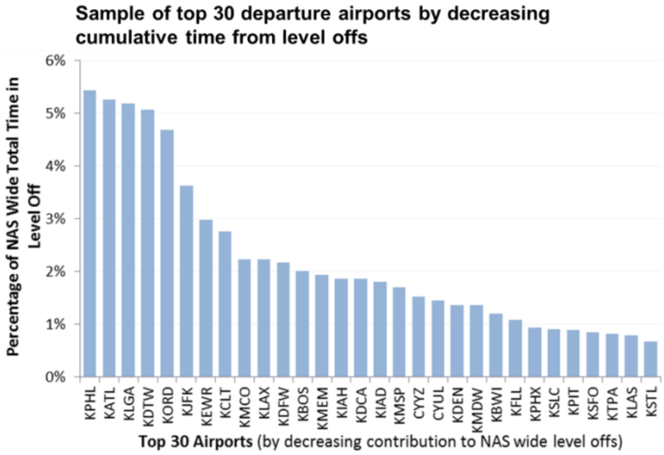

Figure 4. Distribution of Level-offs by Airport.

The distributions of level-off level-offs were also disaggregated by aircraft type categories (i.e., WBs, NBs, and RJs). It was found that over eighty percent of level-offs were generated by NBs and RJs. These aircraft are generally used for U.S. domestic operations.

In addition, it was found that aircraft that conducted level-offs in the climb phase spent on average 4.6% of their climb time in level-offs. The percentage of climb time spent in level-offs varied slightly across these different aircraft types, with both WB and NB spending a slightly larger percentage of climb time in level-offs than RJs, though this variation was found to be small.

Over 60% last less than half a minute, and over 90% of level-offs last less than 1 min. A limited number of long level-offs (i.e. greater than 1 min.) were observed. Only 5% of level-offs last longer than two minutes. Further analysis of the location of level-offs is necessary for both short and long level-offs (longer than four minutes) to identify causes and mitigation options.

As shown in Fig. 5, level-off level-offs tend to concentrate at commonly flown flight levels including FL100, 170, and 230. The identification of these flight levels maps to airspace constraints (i.e., ceilings of terminal area and sector transition airspace).

The frequency of level-offs at each altitude during the climb phase was analyzed. The analysis found that 20% of level-offs took place below 9,000 feet, 60% took place below 17,000 feet, and 80% took place below 23,000 feet. Aside from these commonly used flight levels, level-offs were widely spread across other flight levels.

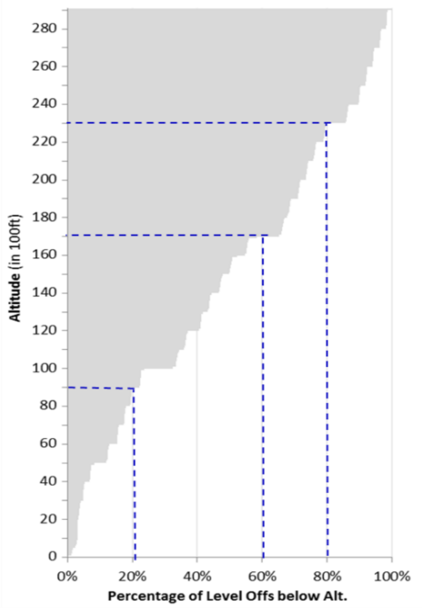

Figure 5. Distribution of altitude of level-offs in the climb phase.

A comparison between NAS operational inefficiencies and potential benefits from improving procedures in the climb vs. descent phases of flight was conducted. It was found that half as many flights are affected by level-offs in the climb phase compared to the descent phase. Overall, the cumulative duration of level-offs in the descent phase is three times larger than in the climb phase.

Level-offs in the climb phase tend to be shorter than in the descent phase. It was found that the average duration of level-offs in the climb phase equated to 35 seconds compared to an average of 1.1 minute in the descent phase. In part, this was explained by the inclusion of holding patterns in the descent phase. The climb phase tends to exhibit a greater number of level-offs (relatively) with short duration. This results in a relatively higher number of acceleration/ deceleration cycles.

However, using the simulation tool Piano5, a level off in the climb phase was found to have 30% greater fuel savings for the B747-400 and 60% greater fuel savings for the B737-700 for level-offs at similar altitude and of the same duration.

The difference is partly explained by the fact that flight operations during the descent phase are generally characterized by throttle and engines running close to idle settings (i.e. low fuel flow levels) and low aircraft gross weights, given that most of the fuel onboard was burnt during the climb and cruise phases [8]. Conversely, in the climb phase, engines tend to run at high thrust settings and aircraft gross weights tend to be higher (compared to the descent phase). As such, fuel burn resulting from operational inefficiencies in the climb and descent phases will differ

Therefore, although half as many operations are impacted by level-offs in the climb phase of flight compared to the descent phase of flight, the level-offs in the climb phase of flight likely have greater potential fuel savings.

IV. Operational and Environmental Benefits Analysis

The previous section established that climb phase level-offs are prevalent throughout the NAS, and removing level-offs results in departure performance improvement. This section of this paper documents the results of an analysis in which in-depth simulation of radar departure data was conducted. The objective is to quantify the potential fuel, operational, emissions and noise impacts of removing level-offs.

Three airports in the NAS were selected in order to conduct the analysis: Los Angeles International Airport (LAX), Denver International Airport (DEN) and Logan International Airport (BOS). These airports fall in the top 30 airports in terms of total time spent in level-off, and are geographically and operationally diverse.

At each airport, Performance Data Analysis and Reporting System (PDARS) track data was collected for 20 days over a one year period. PDARS data provides information on aircraft altitude, latitude, longitude and speed, amongst other information, at up to 1-second intervals. PDARS data has greater fidelity than ETMS data, and therefore AEDT results will have greater accuracy. PDARS comes from Air Route Traffic Control Centers (ARTCCs), Terminal Radar Approach Control (TRACON) facilities and Air Traffic Control Tower (ATCT) facilities.

The baseline radar data was analyzed in terms of departure inefficiency statistics. A script was developed and run in order to develop CCOs on the same tracks. The script sequentially steps through each node in the flight track data. If the node is part of a level-off, then the node altitude is set as the altitude of the node at the end of the level-off. Because the nodes are not equally separated (i.e. the distance between each node varies), linear interpolation is applied to the two nodes after the level-off in order to match the equivalent climb gradient after the level-off. This is an important aspect of the algorithm. It is necessary that the climb gradient at equivalent altitudes in the baseline and modified data is the same. Differences in climb gradient will lead to differences in aircraft performance and therefore anomalies when comparing the datasets.

AEDT was used to compute the fuel burn, emissions and noise impacts of the baseline and CCO set of departure profiles. AEDT is a software system that dynamically models aircraft performance in space and time to produce fuel burn, emissions and noise results. Full flight gate-to-gate analyses are possible for study sizes ranging from a single flight at an airport to scenarios at the regional, national, and global levels. AEDT is currently used by the U.S. government to consider the interdependencies between aircraft-related fuel burn, noise and emissions.

V. Operational and Environmental Benefits Analysis: LAX Results

Twenty days of PDARS data was collected at LAX between August 2012 and May 2013. It was found that 59% of departures in the sample had at least one level-off during the climb phase of flight. In addition, although the total number of departures per day varies depending on the day of the week, the number of flights with level-offs varies to a lesser extent - between 48% and 64% with a standard deviation of 5%.

An additional analysis was conducted in order to quantify the distribution of level-offs by altitude. Fig. 6 shows on the x-axis the percentage of level-offs that occur below the altitude shown on the y-axis. The distribution identifies a concentration of level-offs at 10,000 feet.

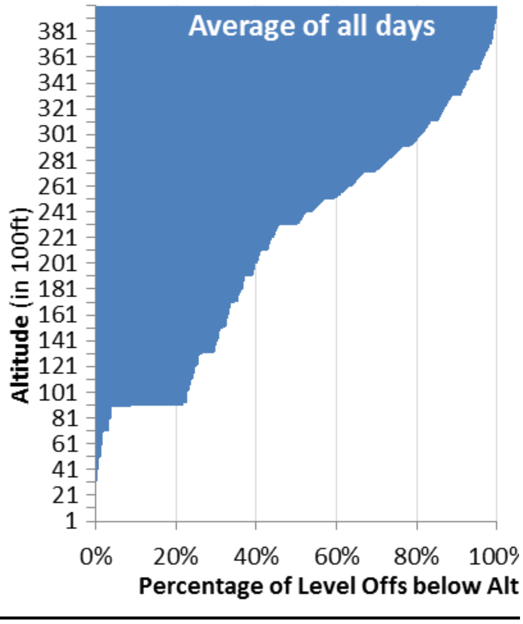

Figure 6. Distribution of level-offs by altitude at LAX.

Additional analysis investigated how the distribution shown in Fig.6 changes at different times of the year. It was found that the airport "signature" level-off altitude distribution changed very little at different times of the year.

Fig. 7 shows that operators were not impacted equally, with some operators having 50% of departures impacted, while others have up to 90% of departures impacted. Level-offs also vary by aircraft type.

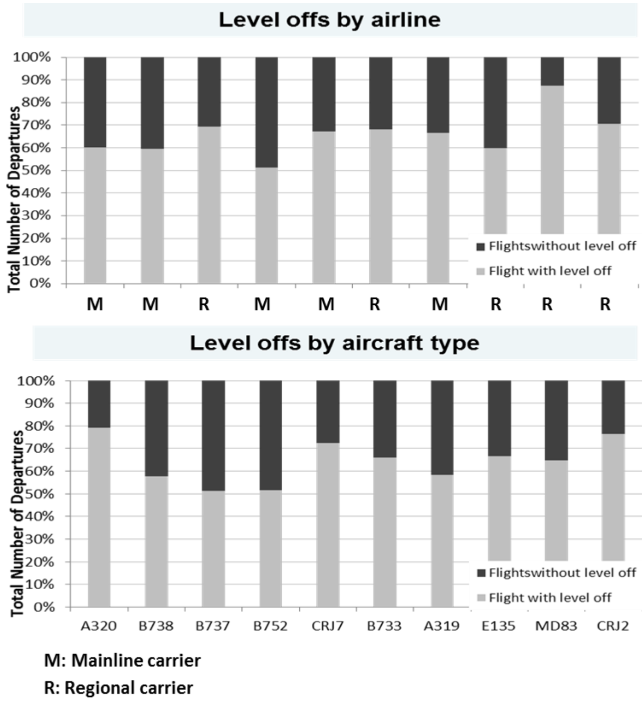

Figure 7. LAX level-off statistics by airline and aircraft type.

One week of data, representing 2010 departures with level-offs, were selected for the AEDT simulation analysis. Fig. 8 shows the distribution in fuel burn and climb time savings for CCO, relative to baseline operations that have level-offs.

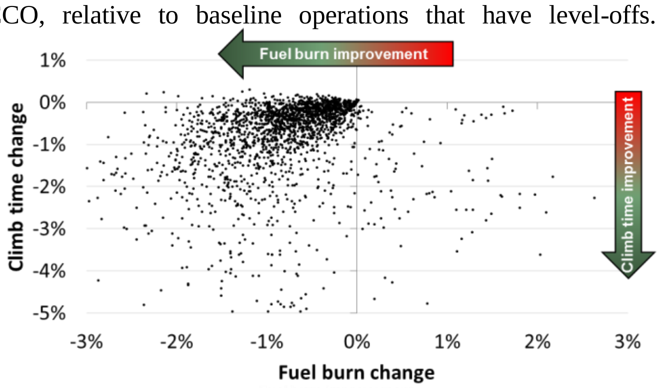

Figure 8. Fuel and climb time impact of Continuous Climb (August 1 – 5 2012).

On average, CCO results in a 0.8% fuel savings and a 0.9% climb time savings. It was found that 87% of operations with at least one level-off had both climb time and fuel benefits.

The average fuel savings from removing level offs at LAX was found to be 0.8% per departure, which equates to approximately 16kg per departure. The average fuel savings of departures with both fuel and climb time savings is 18kg (87% of departures with level-off).

Although one week of data is not necessarily representative of average operations at LAX, an estimation of annual savings can be calculated. Multiplying fuel savings per departure by departures per day and year results in 7 tons fuel savings per day, which translates to 7,360 tons of CO_2 per year or $2 million per year, assuming a fuel price of $2.5 per gallon.

Analysis of the fuel savings data by aircraft type found that Heavy wake category aircraft have the greatest fuel savings potential per departure (129kg max), but comprise only 38% of total fuel savings in the top 20 aircraft types. Large wake category aircraft had lower fuel savings per departure, but comprise a greater number of total operations, and therefore contribute 50% of total savings in the top 20 aircraft types. This suggests that a targeted approach aimed at specific aircraft type/categories could maximize potential fuel savings with minimal airspace change.

Analysis of the breakdown of fuel savings by runway found that there was little variance by runway, with departures off all runways having similar percentage reduction when CCO was implemented, compared to the baseline with level-offs. Because runway 25R and 24L account for the majority of departures at LAX, targeting the operation on these runways would account for the majority of fuel savings.

AEDT was used to calculate both fuel and emissions impacts, as well as noise impacts, in order to identify potential trade-offs between these factors. Fig. 9 shows the noise contours at LAX for one day that is representative of average departures, August 1st 2012. Table 1 maps the color of each contour to its day night average sound level (DNL) value.

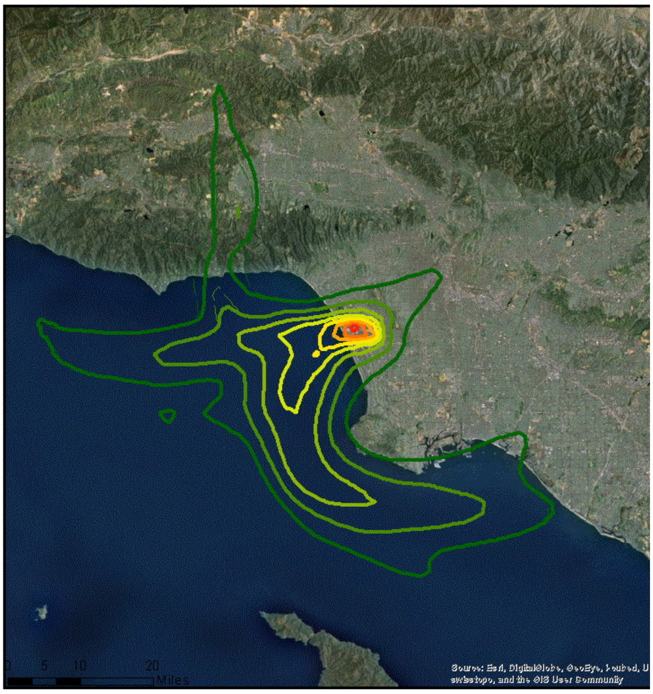

Figure 9. Noise contours of baseline operations (solid contours) and CCO (dashed contours) on August 1 2012.

Table 1. Summary of results from noise contours at LAX.

Noise level (dB DNL)	Baseline with level offs, AREA_SQ_KM	Scenario with CCO, AREA_SQ_KM	Percentage change
40	2249	2239	-0.4%
45	954	973	2.0%
50	440	440	0.0%
55	134	134	0.0%
60	45	45	0.0%
65	26	26	0.0%
70	13	13	0.0%
75	3	3	0.0%

The results were found to be inconclusive, in that very low noise level contours at 40 and 45 dB DNL have both a small increase and decrease in noise exposure. There is no change at higher noise levels.

VI. Operational and Environmental Benefits Analysis: DEN Results

Twenty days of PDARS data was collected at DEN between July 2012 and 2013. It was found that 72% of departures in the sample had at least one level-off during the climb phase of flight. In addition, although the total number of departures per day varies depending on the day of the week, the number of flights with level-offs varies to a less extent - between 60% and 80% with a standard deviation of 7%.

An additional analysis was conducted in order to quantify the distribution of level-offs by altitude. Fig. 10 shows on the x-axis the percentage of level-offs that occur below the altitude shown on the y-axis. The distribution identifies a concentration of level-offs at 9,000 feet, although the concentration is smaller than at LAX, and level-offs are distributed throughout the altitude range to a greater extent.

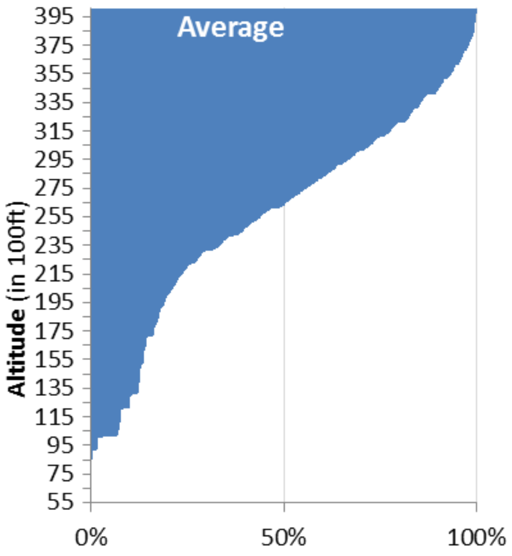

Figure 10. Distribution of level-offs by altitude at DEN.

Additional analysis investigated how the distribution shown in Fig. 10 changes at different times of the year. It was found that the airport "signature" level-off altitude distribution changed very little at different times of the year.

Data showed that operators were not impacted equally, with some operators having ~55% of departures impacted, while others have up to 90% of departures impacted. Level-offs also vary by aircraft type.

One week of data, representing 5,652 departures with level-offs, were selected for the AEDT simulation analysis. Fig. 11 shows the distribution in fuel burn and climb time savings for CCO, relative to baseline operations that have level-offs.

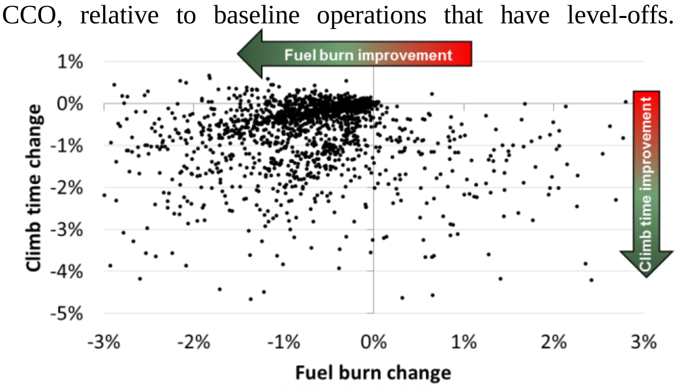

Figure 11. Fuel and climb time impact of Continuous Climb (August 1 – 5 2012).

On average, CCO results in a 1% fuel savings and a 0.8% climb time savings. 67% of operations with a level-off had both climb time and fuel benefits.

DEN mean fuel savings of 1% per operation is about 6kg per departure. The mean fuel savings of departures with both fuel and climb time savings is 10kg (63% of departures with level-off).

Although one week of data is not representative of average operations at DEN, an estimation of annual savings can be calculated. Multiplying fuel savings per departure by departures per day and year results in 3 tons fuel savings per day, which translates to 3,384 tons of CO_2 per year or $0.95 million per year, assuming a fuel price of $2.5 per gallon.

Analysis of the fuel savings data by aircraft type found a similar trend to that of LAX. Heavy wake category aircraft have the greatest fuel savings potential per departure (90kg max), but comprise only 10% of total fuel savings in the top 11 aircraft types. Large wake category aircraft had lower fuel savings per departure, but comprise a greater number of total operations, and therefore contribute towards 27% of total savings in the top 11 aircraft types. This suggests that a targeted approach aimed at specific aircraft types could maximize potential fuel savings with minimal airspace change.

Analysis of the breakdown on fuel savings by runway found that there was little variance by runway, with departures off all runways having similar percentage reduction when CCO was implemented, compared to the baseline with level-offs. Runway 8 and 25 were the most utilized in the sample data, and targeting these two runways would result in more than 50% of total potential fuel savings.

Noise impacts at DEN did not result in a clear trend of benefit or impact, with different days having small but inconclusive noise impacts in the 40-55dB range.

VII. Operational and Environmental Benefits Analysis: BOS Results

Twenty days of PDARS data was collected at BOS between August 2012 and May 2013. It was found that 80% of departures in the sample had at least one level-off during the climb phase of flight. In addition, although the total number of departures per day varies depending on the day of the week, the number of flights with level-offs varies to a lesser extent - between 70% and 90% with a standard deviation of 5%.

An additional analysis was conducted in order to quantify the distribution of level-offs by altitude. Fig. 12 shows on the x-axis the percentage of level-offs that occur below the altitude shown on the y-axis. The distribution identifies a concentration of level-offs at 14,000 feet and 23,000 feet, potentially coinciding with airspace boundaries.

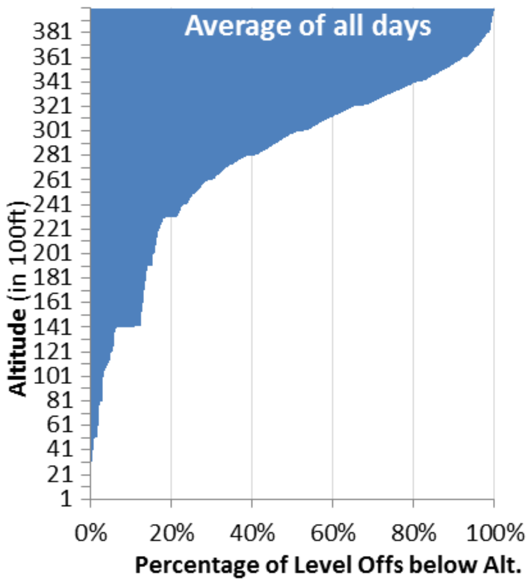

Figure 12. Distribution of level-offs by altitude at BOS.

Additional analysis investigated how the distribution shown in Fig. 14 changes at different times of the year. It was found that the airport "signature" level-off altitude distribution changed very little at different times of the year.

Data showed that operators were not impacted equally, with some operators having ~65% of departures impacted, while others have up to 90% of departures impacted.

One week of data, representing 1473 departures with level-offs, were selected for the AEDT simulation analysis. Fig. 13 shows the distribution in fuel burn and climb time savings for CCO, relative to baseline operations that have level-offs.

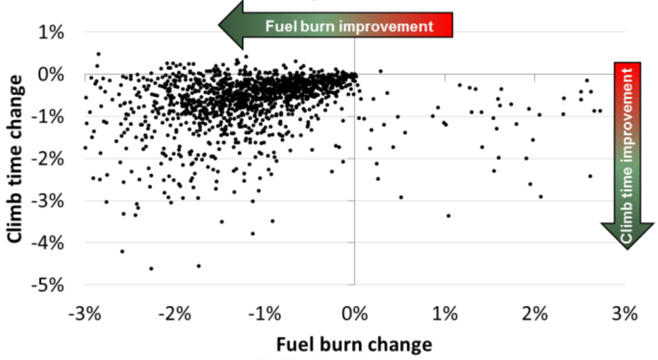

Figure 13. Fuel and climb time impact of Continuous Climb (August 1 – 5 2012).

On average, CCO results in a 1.1% fuel savings and a 0.6% climb time savings. 87% of operations with a level-off had both climb time and fuel benefits.

BOS mean fuel savings of 1.1% per operation is about 19kg per departure with level-off. The mean fuel savings of departures with both fuel and climb time savings is 24kg (87% of departures with level-off).

Although one week of data is not representative of average operations at BOS, an estimation of annual savings can be calculated. Multiplying fuel savings per departure by departures per day and year results in 6 tons fuel savings per day, which translates to 6,971 tons of CO_2 per year or $2 million per year, assuming a fuel price of $2.5 per gallon.

Analysis of the fuel savings data by aircraft type found a similar trend to that of LAX and DEN. Heavy wake category aircraft have the greatest fuel savings potential per departure (108kg max), but comprise only 137% of total fuel savings in the top 20 aircraft types. Large wake category aircraft had lower fuel savings per departure, but comprise a greater number of total operations, and therefore contribute towards 66% of total savings in the top 20 aircraft types. This suggests that a targeted approach aimed at specific aircraft types could maximize potential fuel savings with minimal airspace change.

Analysis of the breakdown on fuel savings by runway found that there was little variance by runway, with departures off all runways having similar percentage reductions when CCO was implemented, compared to the baseline with level-offs. Runway 22R, 22L and 9 were the most utilized in the sample data, and targeting these two runways would result in more than 90% of total potential fuel savings.

Noise impacts at BOS also did not result in a clear trend of benefit or impact in the 40-45dB range.

VIII. Comparison Across Airports and Additional Analyses

Fig. 14 compares average and standard deviation fuel savings at the three airports. LAX and BOS have similar potential fuel savings per departure with level-off, DEN has lower potential fuel savings, potentially because of the greater altitude of its airfield, resulting in shorter climbs and therefore less potential fuel savings.

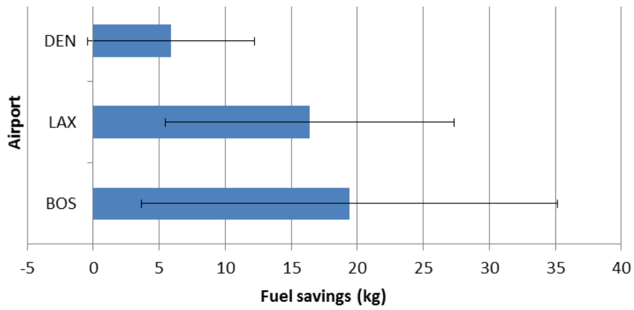

Figure 14. Comparison for fuel savings with CCO by airport.

An analysis at BOS found that targeting a fraction of climb operations can result in a substantial fraction of benefits (Fig. 15). For example, targeting 18% of operations results in 59% of total fuel savings. Previous analysis showed that the operations with greatest potential fuel savings are larger aircraft that may also have the greatest noise impact.

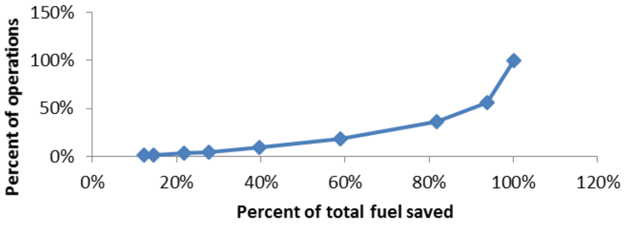

Figure 15. Relationship between fuel savings and percent of operations at BOS.

The three airports had different distributions of level-offs vertically. It is understood that level-offs are related to the specific airspace structure and traffic flows at each airport. There may be noise benefits from removing frequent low altitude level-offs.

Noise analysis documented in earlier sections of this paper used the average noise metric, DNL – which is an average across all departures with and without level offs, over a 24 hour period. Using an average metric may not capture the noise benefits from CCO because the majority of level-offs occur at an altitude at which the changes in amplitude from removing level-offs are not detected in an average metric.

In order to test this hypothesis, a departure was simulated on COORZ2 RNAV Standard Instrument Departure (SID) at DEN. The baseline departure, shown in blue in Fig. 18, includes a level-off of 5 nautical miles between the waypoints LINGT and CRONA, which both have altitude restrictions of below 11,000 feet. The continuous climb does not level-off between these waypoints – shown in red in Fig. 18.

The maximum noise exposure contour (Lmax) was calculated using AEDT. The contours and the change in area are mapped in Fig. 16. The result is an approximate 20% reduction in noise exposure in the range 50 – 65 dB. This suggests that there may be significant noise benefit from continuous climb operations, but that an appropriate noise metric should be used in order to quantify their impact.

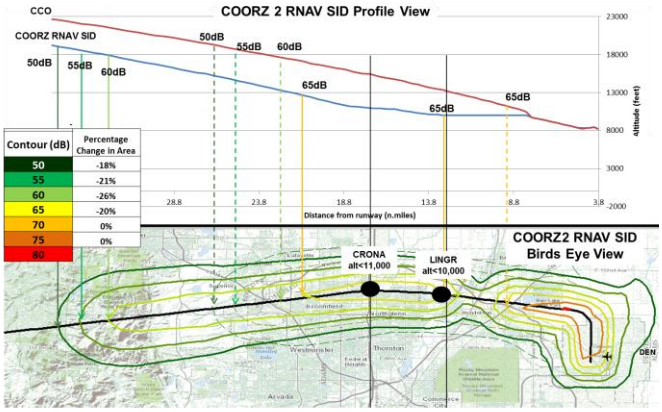

Figure 16. Comparison of level-off climb and CCO at DEN using the maximum noise exposure metric.

While the assessment of fuel savings –described in the sections above- assumed that take off weights remained unchanged, it could be envisaged that a complete and predictable removal of inefficiencies in the climb phase could result in lower fuel reserve/buffer requirements. This reduced buffer fuel load at departure would result in additional fuel savings since this fuel load would not have to be carried throughout the entire flight. An additional analysis was conducted in order to quantify the potential benefit of reducing take-off weight through reduced fuel loads by the fuel savings from CCO. It was found that a B738 flying a 1000 nautical mile mission could save an additional 23% of the fuel savings from removing level-offs if a 10 nautical mile level off at FL100 is removed, and the fuel load is reduced by the saved fuel.

IX. Conclusion

This paper presented an approach for evaluating the current operational inefficiencies in the climb phase. In order to evaluate the frequency of occurrence and magnitude of level-offs in the climb phase, a statistical analysis of NAS-wide inefficiencies in the climb and descent phases was conducted. This analysis was complemented with a geospatial analysis that provided insights into the geographical distribution of inefficiencies in the climb phase across the National Airspace System and in particular at three major airports.

A scoping analysis indicated that on average, three flights out of ten are affected by at least one level-off, and 5% of the climb time is spent maintaining constant altitude. Level-offs tend to distribute uniformly across the entire climb profile, although some flight levels (FLs) are more frequently affected (e.g., FL100, 120, 160, 170, 230, 240). The majority of level-offs last less than 1 minute. Level-offs concentrate at the periphery of a few key airports e.g., Philadelphia International Airport (PHL), Hartsfield-Jackson Atlanta International Airport (ATL), LaGuardia Airport (LGA), Detroit Metropolitan Wayne County Airport (DTW), O'Hare International Airport (ORD), and John F. Kennedy International Airport (JFK).

The scoping analysis presented a similar assessment for the descent phase using the same operational database. Both studies enabled a comparative analysis of the operational inefficiencies and benefits between the climb and descent phases. It was found that half as many flights are affected by level-offs in the climb phase compared to the descent phase. Overall, the cumulative duration of level-offs in the descent phase is three times larger than in the climb phase. It was also found that level-offs in the climb phase tend to be shorter and take place at higher altitudes than in the descent phase.

A detailed operational and energy analysis at Boston Logan International Airport, Denver International Airport and Los Angeles International Airport found that the average potential fuel savings from continuous climb operations range between 6 and 19kg per departure, with annual carbon dioxide savings of 6,970 tons, 3,380 tons and 7,360 tons respectively. Each airport has signature concentrations of level-offs, providing evidence of the role of airspace design and constraints in climb inefficiencies. Change in noise impact is inconclusive using conventional metrics, but alternative metrics showed significant potential noise benefits from CCO. The distribution in fuel savings is skewed, with a few operations having greater than average fuel savings. Implementing continuous climb operations for 18% of operations could result in the capture of 59% of total fuel savings from continuous climb operations.

Potential next steps include additional analyses and stakeholder engagement in order to understand barriers to implementation of CCO, better quantifying annual benefits using an average annual day approach, and additional noise analysis using appropriate noise metrics, in order to fully quantify the benefits and impacts of CCO.

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DISCLAIMER

Any opinions, findings, and conclusions or recommendations expressed in this paper are those of the authors and do not necessarily reflect the views of the U.S. Federal Aviation Administration (FAA).

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