FINAL REPORT
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PROJECT 40

EVALUATION OF CONTINUOUS DESCENT APPROACH IN NORMAL AIR TRAFFIC CONDITIONS

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- Task(s)

  Studies on feasibility of continuous descent arrivals under normal and heavy air traffic.

Project Overview

This project investigates the impact of Continuous Descent Approach (CDA) about the inbound traffic in the terminal airspace. The impact includes fuel consumption and total flight time savings. This project differs from other CDA projects in that it evaluates the CDA under normal air traffic conditions where congested traffic is taken into account. Flying a CDA trajectory increases the risk of potential collision as the pilot may have less control on the aircraft under near idel thrust settings. Evaluation of fuel consumption and flight time only makes sense when the inbound traffic employing CDA is conflict-free. Safety can be guaranteed by employing conflict detection resolutions (CDR). Although tactic manuevers, such as heading change, horizontal speed change, and vertical speed change, are able to solve the most immediate collision, they potentially interrupt the near idel thrust settings. Consequently, the CDA trajectory is aborted. In this project, a strategic solution is developed which sequences the arriving aircraft under minimum separation constraints as well as miles-in-trail constraints. In addition to inter-aircraft separation, this project also takes into account the mutual interference between streams flowing into airports of a metroplex. The fuel consumption and delay for deconfliction are counted when the fuel and flight time savings are evaluated. The proposed CDR is applied to the major airports and metroplex airports in the United States. Fuel statistic and flight time are obtained from the *Future ATM Concept Evaluation Tool* (FACET). By comparing the conflict-free CDA to the conflict-free Step-down approach, the benefits of CDA as well as the associated trade-off are quantified.

Investigation Team

Dengfeng Sun received bachelor degree in precision instruments and mechanology from Tsinghua Unviersity, China, master degree in industrial and systems engineering from the Ohio State University, and PhD degree in civil engineering from the University of California - Berkeley. Dr. Sun's research areas include control and optimization, with an emphasis on applications in air traffic flow management, dynamic airspace configuration, and studies for the Next Generation Air Transportation Systems.

Daniel DeLaurentis is an Associate Professor in Purdue's School of Aeronautics & Astronautics in West Lafayette, IN. Dr. DeLaurentis leads the System-of-Systems Laboratory (SoSL) which includes graduate and undergraduate students as well as professional research staff. His primary research interests are in the areas of problem formulation, modeling and system analysis methods for aerospace systems and systems-of-systems (SoS), with particular focus on air transportation. His research is conducted under grants from NASA, FAA, Navy, and the Missile Defense Agency. Dr. DeLaurentis is an Associate Fellow of the American Institute of Aeronautics and Astronautics, served as Chairman of the AIAA's Air Transportation Systems (ATS) Technical Committee from 2008-2010, and is Associated Editor for the IEEE Systems Journal. He earned a PhD in Aerospace Engineering from the Georgia Institute of Technology (Atlanta, GA) in 1998.

Joseph Post is the director of systems analysis in the Federal Aviation Administration's NextGen and Operations Planning organization. He received bachelor degree in aeronautics and astronautics from the Massachusetts Institute of Technology, master degree in electrical engineering from Yale University, and master degree in economics from George Mason University. Mr. Post holds numerous patents in the area of automatic flight control systems and is an instrument-rated pilot.

Tatsuya Kotegawa is a graduate research assistant in the System-of-Systems Laboratory and a PhD candidate in the School of Aeronautics and Astronautics at Purdue University. He received his BS and MS in Aeronautics and Astronautics Engineering from Purdue in 2006 and 2008. His research interest lies in developing foundational methods and tools for addressing problems seen in large-scale, complex systems, often characterized as system-of-systems.

Yi Cao is pursuing the PhD degree at the School of Aeronautics and Astronautics, Purdue University. He received bachelor degree in Instrumentation Science and Engineering in 2006, and master degree in Navigation, Guidance and Control in 2009 from Shanghai Jiao Tong University, China. His research mainly focuses on modeling, optimization, simulation, with an emphasis in air traffic flow management.

Task # Task Title

Project 40 | Continuous Descent Arrival National Operational Feasibility

Objective(s)

The objective of this project is to quantify the fuel savings of conflict-free CDAs in normal terminal airspace operations. Effort is taken to understand what the trade-off would be if current Step-down approach is replaced by CDA. The overarching goal of this project is to examine the feasibility of CDA nationally, in particular to provide a better estimate of the prospective benefits.

Research Approach

Due to the high cost for field test, it is impossible to evaluate CDA nationally by practice. Therefore, a simulation-based assessment is the only way to provide an initial estimation. In this project, FACET is used as the simulation platform, which can simulate and visualize the enroute traffic as well as the inbound traffic recorded by the ASDI data. FACET has a build-in aircraft performance database. Using the information associated with a specific aircraft type, the fuel and flight time of every recorded flight can be estimated. Moreover, FACET provides a variety of JAVA APIs enabling one to develop customized algorithm and incorporate it into a simulation.

In order to evaluate CDA, two scenarios are set up. In the first scenario, the flight descends along a CDA trajectory; in the second scenario, the flight descends along a Step-down trajectory. In both scenarios the ground tracks are the same. The only difference is the vertical decent profile, which results in different fuel consumption and flight time.

Figure 1 shows a flowchart of the simulation which is designed to obtain the data for benefit evaluation. First, the ASDI data is fed into FACET. FACET runs in a *Simulation* mode where filed flight plans are used in conjunction with the aircraft performance database to simulate the traffic. Simulated trajectories are the output from this simulation. The sequencing algorithm is programmed in C++, and then the simulated trajectories are processed. Delay assignment to each flight is obtained from the sequencing algorithm. The simulation is run again where the delay assignment is also fed into FACET in conjunction with the flight plans. A build-in confliction detection module can verify whether the traffic is conflict-free. The fuel consumption and flight time can be recorded as well in this simulation.

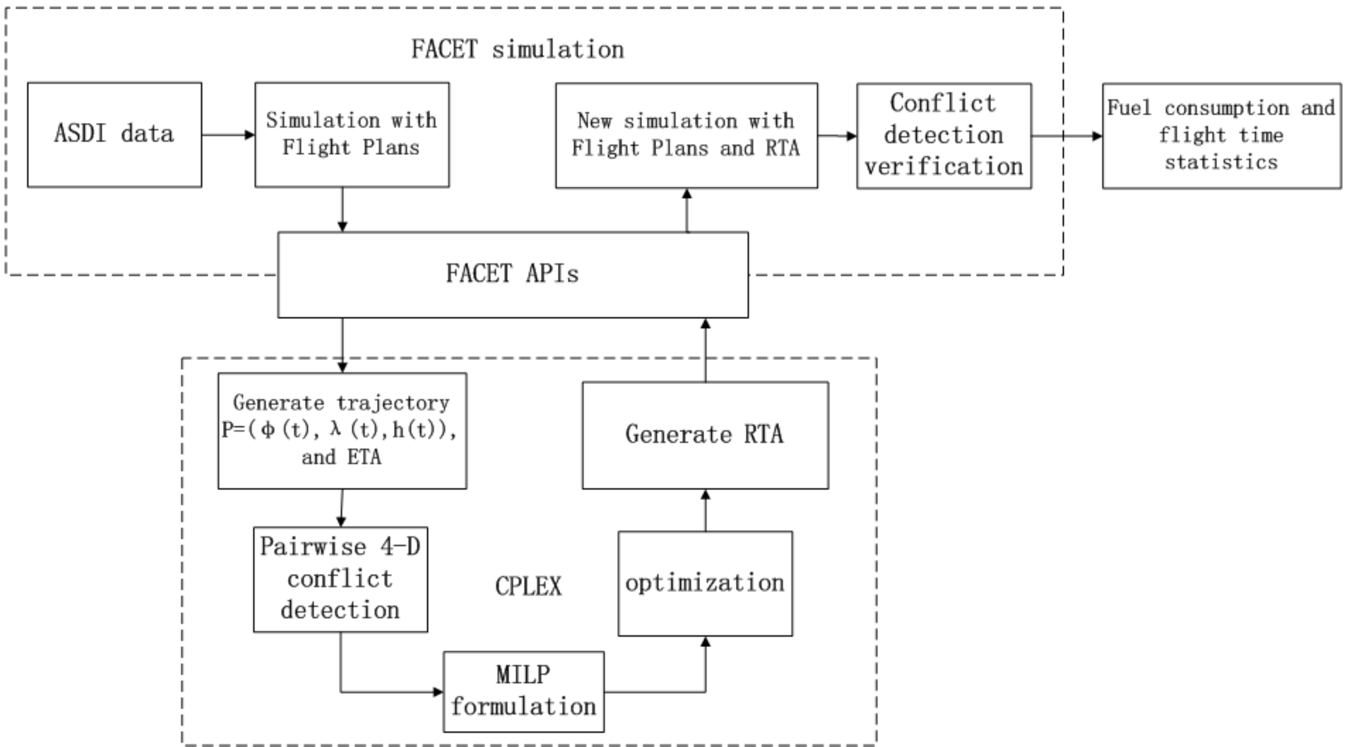


Figure 1 Flow chart of simulation

Milestone(s)
N/A.

Specific works involved in the simulation are listed as follows.

1. ***Vertical profile design*** (August ~ October, 2010, completed).

   By default FACET uses CDA profile to propagate the descent trajectory of an arriving aircraft. A conventional Step-down profile must be designed to provide a baseline. Using the APIs, all aircraft can be programmed to fly the Step-down trajectories. With the Step-down and CDA profiles, the fuel and flight time can be compared.

   There is no formal definition for the Step-down approach in literature since the trajectory of a Step-down approach is contingent with various practical factors, such as traffic condition in the destination airport, aircraft type, wind and so on. A typical Step-down approach involves the following elements:

(a) The arriving aircraft start descending when it reaches the calculated Top of Descent (TOD).

(b) There are several level-offs during the descent procedure.

(c) The level-offs are usually between 5,000~10,000 ft, and 20 nautical miles (nm) distant from the touchdown.

(d) The aircraft intercepts the final 3° ILS glide path at an appropriate distance from the touchdown.

In FACET, the position of TOD is calculated using the preset airspeed of a particular aircraft type. In the *Simulation* mode, effects of wind and interference between aircraft are not considered. A vertical profile of CDA is a smooth glide slope stretching from the TOD to the touchdown. A Step-down profile can be obtained by modifying the corresponding CDA profile. Two level-offs are added between 60~70 nm and 30~40 nm distance from the touchdown, with each has a length of approximately 10 nm. To compensate the level-offs, the TOD must start 20 nm earlier than it does in CDA. Figure 2 shows the vertical decent (?) profiles of two aircraft types simulated by FACET. Generally, the higher an aircraft cruises, the further away its TOD is from the actual touchdown. For LJ35 which is a small aircraft, its cruise altitude is (Is it better to have the real number here?). Thus its TOD is only 40 nm distance from the touchdown in CDA, consequently one level-off is added. In case the TOD is too close to the touchdown to accommodate a level-off, no level-off will be added. Therefore, in the Step-down simulation, the number of level-off of an arriving aircraft is determined by the position of its TOD in CDA simulation.

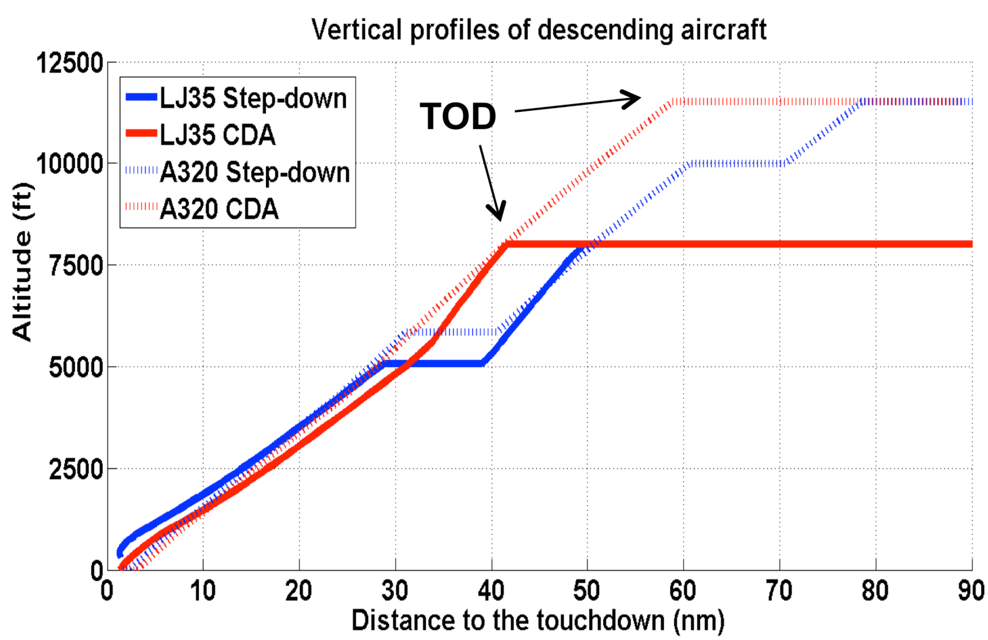


Figure 2 Vertical profiles of two aircraft types in CDA and Step-down approach

Figure 3 shows the fuel consumption of the A320 presented in Figure 2. It reveals the secret of fuel savings by CDA. The upper subfigure compares the fuel flow rate. CDA avoids low altitude levels by cruising at high altitude as long as possible. The fuel flow rate at low altitude is higher than that at high altitude. Therefore, CDA saves fuel, which is validated by the lower subfigure. It is worth noting that the fuel flow rate of a particular aircraft type is only a function of altitude in the simulation, which is somewhat ideal. But the observation is consistent with conclusions from other CDA research. Hence, the result provides a sound estimation to the reality.

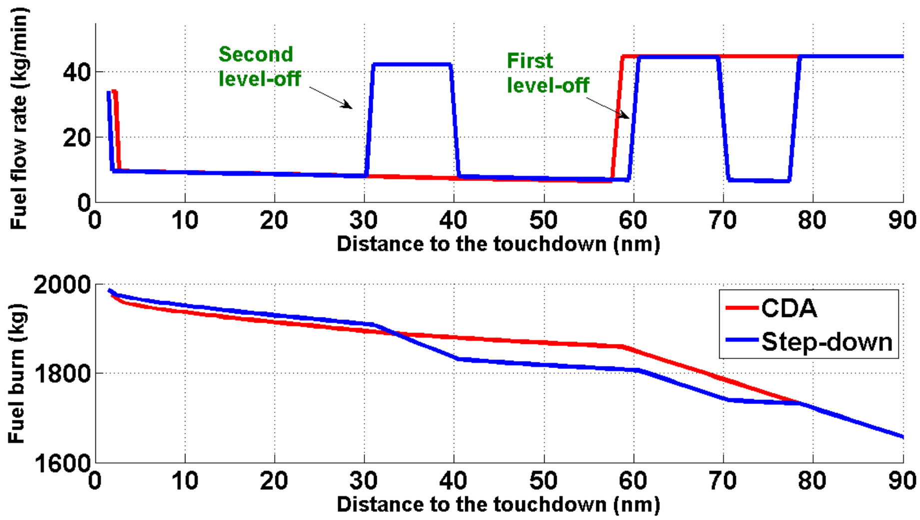


Figure 3 Fuel consumption of an A320 aircraft

2. ***Traffic analysis*** (September ~ October, 2010, completed).

With the CDA profiles and Step-down profiles, we are able to assess the impact of CDA on the inbound traffic. Amongst various issues, safety comes first. We are interested to know what it would be if current Step-down could be replaced by CDA.

In the *Simulation* mode, all aircraft stick to their flight plans and preset performance settings associated with aircraft types. In other words, inter-aircraft interference is not taken into account in the navigation. As a result, conflicts occur frequently. The minimum separation between flights for enroute traffic is 5 nm for horizontal separation and 1,000 ft for vertical separation below FL290, or 2,000 ft above FL290. In the terminal airspace, the horizontal separation is commonly reduced to 3 nm. However, from the perspective of air traffic control, a 5 nm separation provides more buffer to accommodate uncertainties in congested traffic. For illustration purpose, the separation is generally outlined by a cylindrical protected zone around an aircraft, as shown in Figure 4. If the protected zone of two aircraft has intersection, a conflict alert is issued.

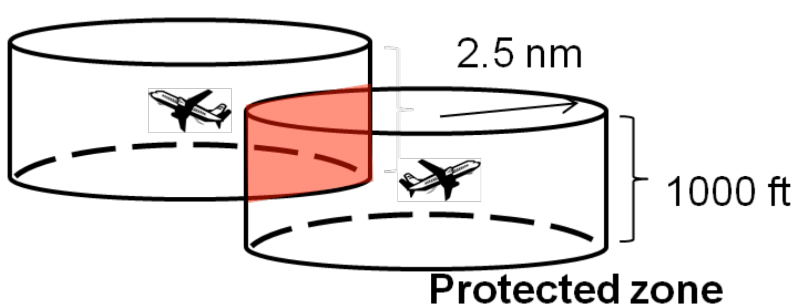


Figure 4 Minimum separation

Figure 5 shows the simulated traffic in Newark Liberty International Airport on August 23, 2005, which compares the total number of confliction versus altitude. Data shows that flying CDA leads to more conflicts than flying Step-down. The number of conflicts is counted in a way such that if two aircraft are in conflict for 5 minutes the conflict count increases by 5. It is observed that the conflict count increases as the flight level decreases. This is due to the fact that large volume of traffic funnel through the limited airspace around the vicinity of airport. In both scenarios, aircraft enjoy the “free flight” where the arriving aircraft are not subject to any sequencing control when approaching the runway. Consequently, the conflict count becomes very large below FL30. Between FL80 and FL 30 where aircraft level off when flying Step-down trajectories, the conflict count is lower than that in CDA scenario. This suggests that level-off provides more space for staggering the arriving aircraft vertically. Replacing Step-down with CDA would reduce the degree for spacing aircraft.

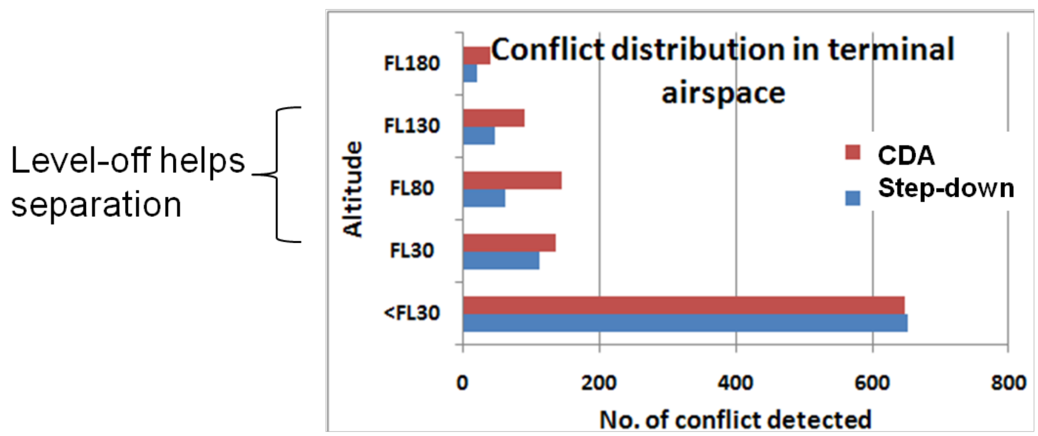


Figure 5 Conflict distribution in the terminal airspace around EWR on Aug 23, 2005

3. ***Development of the sequencing algorithm*** (October ~ January, 2011, completed).

The evaluation of benefits makes sense only when CDA meets the basic requirements of terminal airspace operations. In this project, the following constraints are applicable:

(a) The arriving flow is conflict-free.

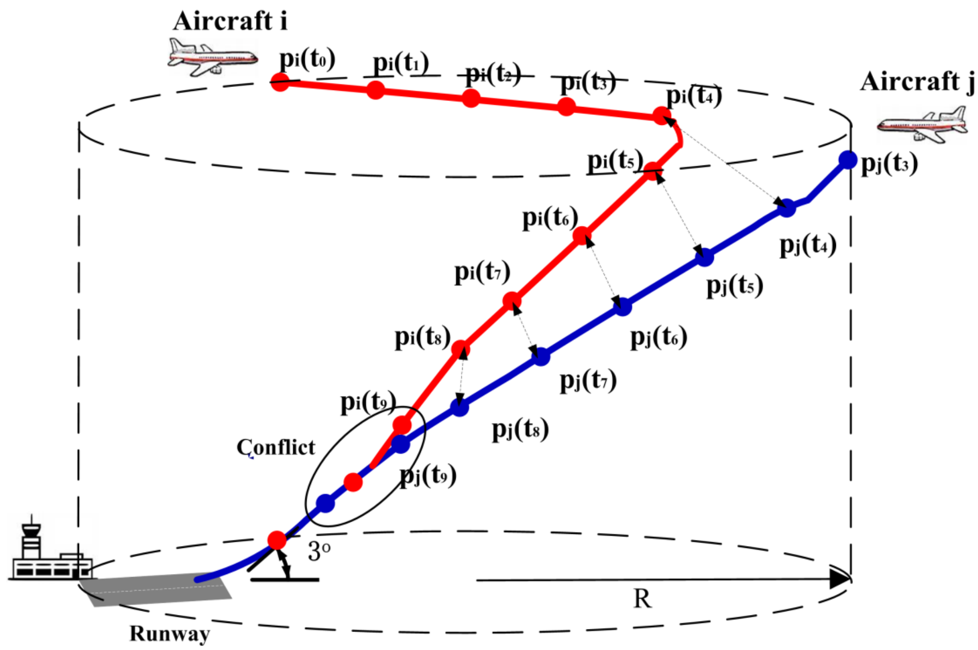
(b) The runway capacity is respected.

(c) Cross-over traffic of Metroplex airports is de-conflicted.

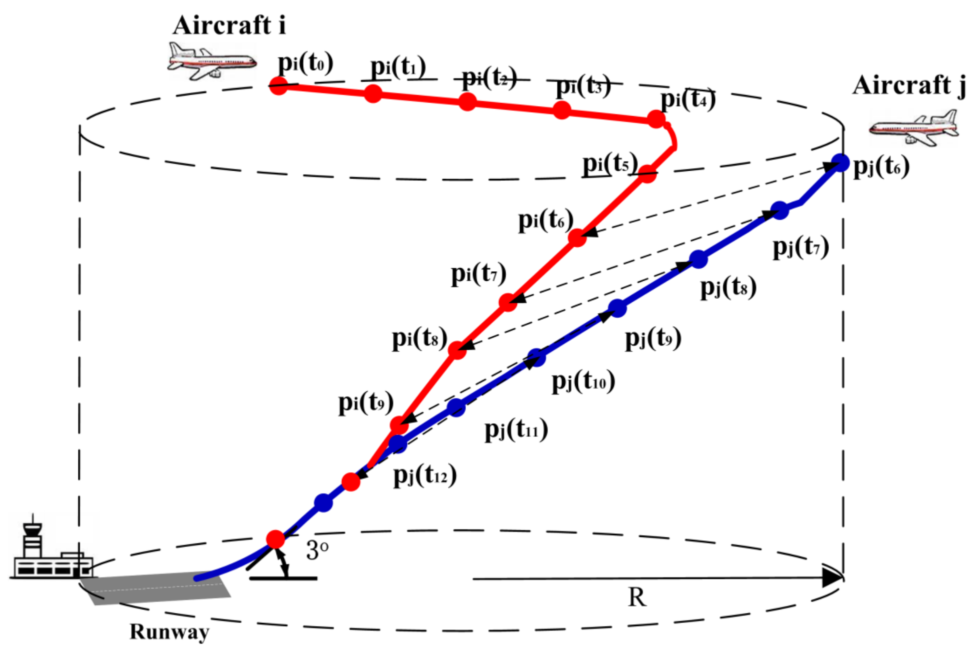
The solution is a sequencing algorithm. An arriving aircraft is in near idle thrust setting when performing CDA. Any tactic operation inclines to interrupt CDA. Hence, an arriving flow should be strategically sequenced such that all aircraft can follow their preset trajectories and the corresponding schedules. Constrained Position Shifting (CPS) is an ideal conflict resolution for CDA which can preserve the continuous descent trajectories. An aircraft simply delays its arrival at the terminal airspace to avoid potential conflicts. Thus the manipulation is finished before descending process begins. The focus is how to determine the delay the aircraft need to achieve a conflict-free CDA. An optimization method is developed for sequencing the arriving flow.

(a) Constrained Position Shifting

This project is focused on conflicts that would occur in the terminal airspace only. Figure 6 shows the ideal picture of constrained position shifting. A cylindrical region with a radius ***R*** centered in the airport is defined. The terminal airspace refers to the space within this region. ***R*** is determined in a way such that majority of the flights initiate the descending procedures within the terminal airspace where they are subjected to separation constraints. In most cases, ***R*** is set to be 180 nm. It is assumed that the flights are equipped with the 4-D capable FMSs and able to fly the pre-determined 4-D trajectories. Then each flight can be predicted with its descent trajectory when it is still airborne. With the predicted trajectory, it is possible to check potential conflicts. If two aircrafts are predicted to conflict in the terminal airspace, one of them will be delayed such that their arrivals are staggered in time, as illustrated in Figure 6 (b).



a) Conflict detected based on the predicted 4-D trajectories



b) Conflict solved by delaying one of the aircraft

Figure 6 Illustration of constrained position shifting

The sequencing algorithm is developed to find the optimal landing sequence which minimizes the total delay. An arriving aircraft set is denoted as $\boldsymbol{A} = [\boldsymbol{A}_1, \boldsymbol{A}_2, \cdots, \boldsymbol{A}_N]$. Initially, arriving flights independently plan their trajectories according to their flight plans without considering mutual interferences. For flight $\mathbf{A}_i$ and $\mathbf{A}_j$, their 4-D trajectories within the terminal airspace are of interest, which are a discretization of the trajectories:

$$\boldsymbol{P}_i(\boldsymbol{t}_0^i,\boldsymbol{t}_n^i) = [\boldsymbol{p}_i(\boldsymbol{t}_0^i,\varphi_0^i,\lambda_0^i,\boldsymbol{h}_0^i), \boldsymbol{p}_i(\boldsymbol{t}_1^i,\varphi_1^i,\lambda_1^i,\boldsymbol{h}_1^i),\ldots, \boldsymbol{p}_i(\boldsymbol{t}_n^i,\varphi_n^i,\lambda_n^i,\boldsymbol{h}_n^i)]$$

$$\boldsymbol{P}_j(\boldsymbol{t}_0^j,\boldsymbol{t}_n^j) = [\boldsymbol{p}_j(\boldsymbol{t}_0^j,\varphi_0^j,\lambda_0^j,\boldsymbol{h}_0^j), \boldsymbol{p}_j(\boldsymbol{t}_1^j,\varphi_1^j,\lambda_1^j,\boldsymbol{h}_1^j),\ldots, \boldsymbol{p}_j(\boldsymbol{t}_n^j,\varphi_n^j,\lambda_n^j,\boldsymbol{h}_n^j)]$$

where $\boldsymbol{p}_i(\boldsymbol{t}_0^i,\varphi_0^i,\lambda_0^i,\boldsymbol{h}_0^i)$ is the first waypoint where $\mathbf{A}_i$ arrives at the boundary of terminal airspace at time $\boldsymbol{t}_0^i$, and $\boldsymbol{p}_i(\boldsymbol{t}_n^i,\varphi_n^i,\lambda_n^i,\boldsymbol{h}_n^i)$ is the last waypoint where $\mathbf{A}_i$ finishes landing at time $\boldsymbol{t}_n^i$. $\varphi_1^i,\lambda_1^i,\boldsymbol{h}_1^i$ is the latitude, longitude and altitude respectively. The waypoint list is, in fact, a temporal and spacial discretization of the trajectory with an interval $\Delta\boldsymbol{T}$. $\mathbf{A}_i$ and $\mathbf{A}_j$ are present in terminal airspace in time windows $[\boldsymbol{t}_0^i,\boldsymbol{t}_n^i]$ and $[\boldsymbol{t}_0^j,\boldsymbol{t}_m^j]$ respectively. If $[\boldsymbol{t}_0^i,\boldsymbol{t}_n^i]$ and $[\boldsymbol{t}_0^j,\boldsymbol{t}_m^j]$ intersect in some time window $[\boldsymbol{t}_p,\boldsymbol{t}_q] = [\boldsymbol{t}_0^i,\boldsymbol{t}_n^i] \cap [\boldsymbol{t}_0^j,\boldsymbol{t}_m^j]$, trajectories of these two flights must be checked for potential conflicts. A conflict detection function is defined:

$$\boldsymbol{CD}(\boldsymbol{i},\boldsymbol{j},\boldsymbol{t}_p,\boldsymbol{t}_q) = \sum_{\boldsymbol{t}=\boldsymbol{t}_p}^{\boldsymbol{t}_q} \boldsymbol{C}(\boldsymbol{p}_i(\boldsymbol{t},\varphi_0^i,\lambda_0^i,\boldsymbol{h}_0^i), \boldsymbol{p}_j(\boldsymbol{t},\varphi_0^j,\lambda_0^j,\boldsymbol{h}_0^j)) \tag{1}$$

$$\boldsymbol{C}(\boldsymbol{p}_i(\boldsymbol{t},\varphi_0^i,\lambda_0^i,\boldsymbol{h}_0^i), \boldsymbol{p}_j(\boldsymbol{t},\varphi_0^j,\lambda_0^j,\boldsymbol{h}_0^j)) = \begin{cases} 0 \ \text{ if } \left|\boldsymbol{h}_t^i - \boldsymbol{h}_t^j\right| \geq \boldsymbol{H} \\ 1 \ \text{ if } (\left|\boldsymbol{h}_t^i - \boldsymbol{h}_t^j\right| < \boldsymbol{H}) \,\&\&\, (\boldsymbol{d} < \boldsymbol{D}) \end{cases} \tag{2}$$

$$\boldsymbol{d} = 2\boldsymbol{r} \times \arcsin\left(\sqrt{\sin^2(\frac{\Delta\varphi}{2}) + \cos\varphi_i \cos\varphi_j \sin(\frac{\Delta\lambda}{2})}\right) \tag{3}$$

where $\boldsymbol{r}$ is the radius of the earth. $\boldsymbol{d}$ is the great-circle distance between two waypoints computed using the *haversine* formula shown in Eq. (3). $\boldsymbol{H}$ and $\boldsymbol{D}$ are the minimum vertical and horizontal separations respectively. Generally, $\boldsymbol{D} = 5$ nm. $\boldsymbol{H} = 2{,}000$ ft if flights are above FL290 and $\boldsymbol{H} = 1{,}000$ ft if flights are below FL290. From Eq. (2), if two aircraft lose separation on their waypoints, $\boldsymbol{CD}(\boldsymbol{i},\boldsymbol{j},\boldsymbol{t}_p,\boldsymbol{t}_q)$ is nonzero. An intuitive method to de-conflict the flights is to assign delays to one of the two flights to stagger them. Suppose $\mathbf{A}_i$ is delayed by Δt, then a delayed 4-D trajectory of $\mathbf{A}_i$ is generated as follows:

$$P_i(t_0^i + \Delta t, t_n^i + \Delta t) = [p_i(t_0^i + \Delta t, \varphi_0^i, \lambda_0^i, h_0^i), p_i(t_1^i + \Delta t, \varphi_1^i, \lambda_1^i, h_1^i), \ldots, p_i(t_n^i + \Delta t, \varphi_n^i, \lambda_n^i, h_n^i)]$$

Note that $P_i(t_0^i + \Delta t, t_n^i + \Delta t)$ is simply a shift of the original $P_i(t_0^i, t_n^i)$ in time, i.e., $\mathbf{A}_i$ will pass the original waypoints with a delay of Δt. Due to the delay, the intersection of time window changes to $[t'_p, t'_q]$. If the trajectory of the aircraft is sufficiently shifted, then, one can ensure that $[t'_p, t'_q] = \phi$, or $CD(i, j, t_p, t_q) = 0$. Essentially, one can resolve the conflict between the aircraft by suitably delaying the entry time of the aircraft into the region. The proposed scheduling method is essentially a trajectory-based resolution which can be applied to both CDA and Step-down.

In a busy traffic environment, delaying one aircraft may result in additional conflicts with other aircraft. The objective is to determine the minimum delays needed to de-conflict the inbound traffic. Such problems can be formulated as a Mixed Integer Linear Program (MILP).

(b) Mixed Integer Linear Program Formulation

Define a decision variable vector for each aircraft:

$$w^i = [w_0^i, w_1^i, \ldots, w_L^i], \quad i \in \{1, 2, \ldots, N\} \tag{4}$$

where w_k^i is a binary variable. w^i means there are L possible delay solutions assigned to $\mathbf{A}_i$, each with a delay of $k\Delta T$. If $\mathbf{A}_i$ is assigned the k^{th} delay, $w_k^i = 1$; other decision variables associated with $\mathbf{A}_i$ are zero. The maximum delay allowed is $L\Delta T$.

The goal is to minimize the total delay. The objective function is as follows:

$$\min \sum_{i=1}^{N} \sum_{k=0}^{L} c^i w_k^i k \Delta T \tag{5}$$

The objective function shown in Eq. (6) is the weighted delay. c^i is the weight given consideration to the fairness among flights. If the objective is to minimize the fuel consumption, c^i can be set to the fuel flow rate. The objective function is subject to:

$$\sum_{k=0}^{L} w_k^i = 1 \tag{6}$$

$$w_k^i \in \{0,1\} \tag{7}$$

$$\begin{aligned} &\textbf{if } ([t_p, t_q] \neq \phi \;\&\&\; CD(i, j, t_p, t_q)) \\ &\textbf{then set: } \mathbf{w}_{k_i}^i + \mathbf{w}_{k_j}^j \leq 1 \end{aligned} \tag{8}$$

$$i, j \in \{1, 2, \ldots, N\}, \quad k_i, k_j \in \{0, 1, \ldots, L\}$$

Eq. (7) means each flight can only be assigned to one delay solution. Eq. (8) is the binary constraint. Eq. (9) is the conflict detection constraint. Suppose two flights are assigned delays $k_i \Delta T$ and $k_j \Delta T$ respectively ($w_{k_i}^i = 1$ and $w_{k_j}^j = 1$). Then their delayed 4-D trajectories are checked. If there are conflicts, Eq. (9) guarantees that such assignment is infeasible. Essentially, the algorithm enumerates all the possible delay assignments, and uses the MILP to determine which one leads to the minimum cost.

The maximum amount of delays L is critical to the existence of a feasible solution. If L is too small, it is not able to separate aircraft in conflict even with the maximum delay. If L is too large, there must be a feasible solution (in the worst case, flights are sequenced to fly into the terminal airspace one by one). However, the dimension of the problem could grow to an extent that it may be very difficult to solve computationally. Hence, to search for a minimum feasible delay assignment, we start the simulation by choosing a small value of L (≈ 10). If the optimization is infeasible, the algorithm increases L by 1, and starts a new run. The algorithm does not stop until there is a feasible solution.

(c) Minimum in-trail separation

The scheduling algorithm solves conflicts during the descents, but it does not evaluate the arrival capacity of the airport. Each airport has a maximum capacity which varies upon runway configurations and local terrain. The arrival flow must be sequenced to meet the capacity bound by requiring a minimum in-trail separation between successive arrivals. For example, the typical benchmark rate of EWR is 40 landings per hour, which is equivalent to 1.5 minutes per landing. The final solution must guarantee that the landing intervals are not less than this minimum in-trail separation. One more step is added to accomplish this after obtaining the delay assignment for CDA separation.

By the scheduling algorithm, the landing time of $\mathbf{A}_i$ is obtained:

$$t_{landing}^i = t_n^i + \sum_{k=0}^{L} w_k^i k \Delta T$$

With delays, the flights arrive in a new order. First, the new time of arrival $t_{landing}^i$ are sorted in a non-decreasing order using the *Bubble Sort* algorithm. Then successive arrivals are checked for the minimum in-trail separation. Suppose that $\mathbf{A}_j$ lands next to $\mathbf{A}_i$:

$$\textbf{if} \quad (t^j_{landing} - t^i_{landing} < \Delta T_{min.\,in-trail})$$

$$t^j_{landing} = t^i_{landing} + \Delta T_{min.\,in-trail}$$

where $\Delta T_{min.\,in-trail}$ is the minimum in-trail separation measured in time. This process finally produces another new arrival sequence that respects both the conflict separation constraints and arrival rate constraints. The complete algorithm is listed in Table 1.

Table 1 Sequencing algorithm

1. Initialization:

L = small positive integer

Generate planned 4-D trajectory of A_i: $[t^i_0, t^i_n]$ and $P_i(t^i_0, t^i_n)$

3. Formulation and Iteration:

do{

$L = L + 1$

generate: $w^i = [w^i_0, w^i_1, \ldots, w^i_L]$

interval: $[t^i_0 + w^i_k k\Delta T, t^i_n + w^i_k k\Delta T]$

delayed 4-D trajectory: $P_i(t^i_0 + w^i_k k\Delta T, t^i_n + w^i_k k\Delta T)$

Optimize: $\min \sum_{i=1}^{N} \sum_{k=0}^{L} c^i w^i_k k\Delta T$

s.t. $\sum_{k=0}^{L} w^i_k = 1$

$w^i_k \in \{0, 1\}$

if $([t_p, t_q] \neq \emptyset \ \&\& \ CD(i, j, t_p, t_q) > 0)$

$w^i_{k_i} + w^j_{k_j} \leq 1, \qquad i, j \in \{1, 2, \cdots, N\}$

end if

} ***while***(infeasible solution)

4. Output: $w^i = [w^i_0, w^i_1, \ldots, w^i_L], \qquad i \in \{1, 2, \cdots, N\}$

5. Order the landing time of arrivals with delays from step 4 with the Bubble sort.

6. Check and impose minimum in-trail separation.

7. Output: final landing times $\{t^i_{landing}\}, \qquad i \in \{1, 2, \cdots, N\}$

Figure 7 shows the arrival with and without in-trail separation; JFK encounters high traffic between 20:00 and 24:00 when the arrivals are nearly twice as the benchmark rate. This accounts for the high amount of delays that JFK receives. The arrivals are so intensive that many flights have to be delayed before entering the terminal airspace and wait for landing services. EWR and LGA do not encounter such a burst during the peak hours. But EWR has a high level of traffic above the benchmark rate, thus it needs a higher amount of delays to control the arrival rate than LGA.

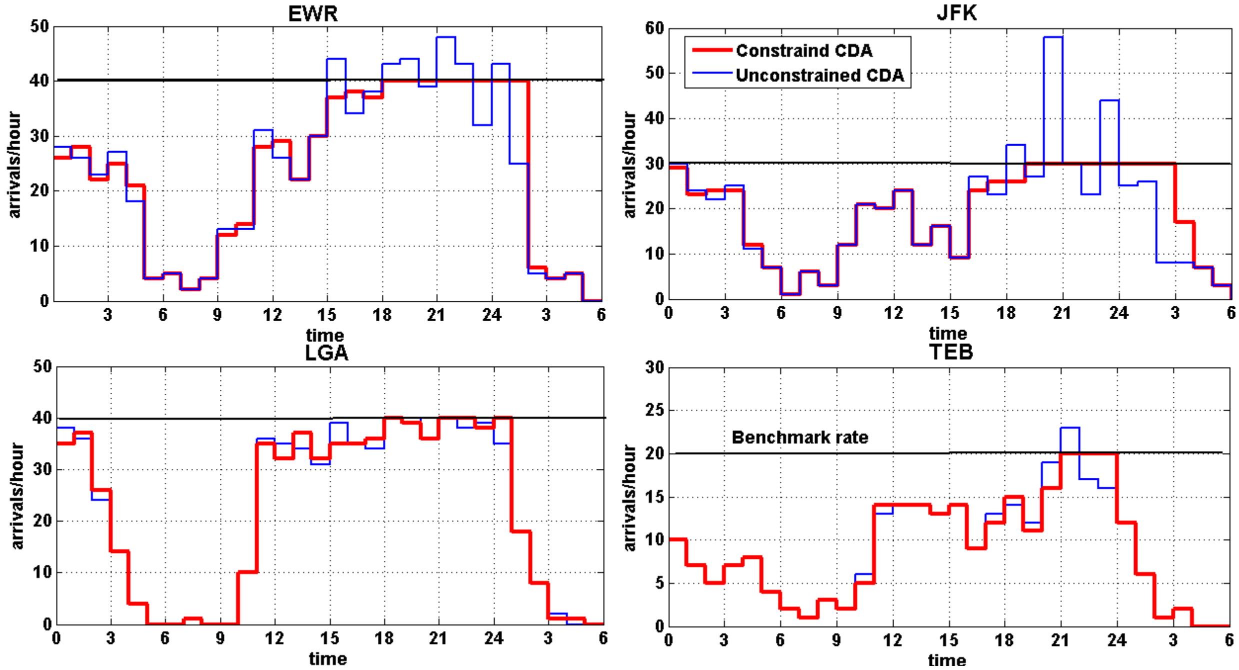
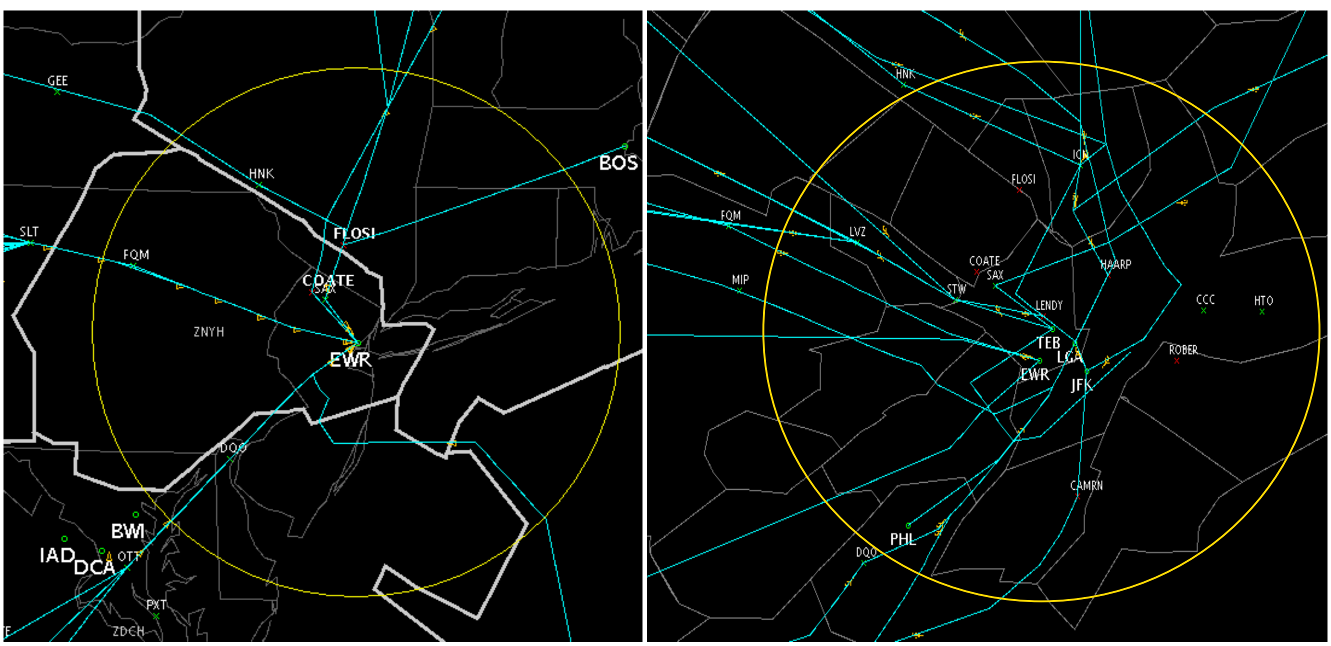


Figure 7 Airport arrivals with in-trail separation



a) Single airport b) Metroplex airports

Figure 8 Cross-over traffic in metroplex airports

(d) Practical concerns

For long distance flight, aircraft generally begin descending 150 nm distant away from the touchdown airport. Delay control must be effective before descending. Therefore, the affected traffic covers a vast area. Figure 8 (a) shows the arriving flows around EWR. The yellow circle has a radius of 180 nm and covers a vast area. Arriving flights flow into EWR mainly from three directions. The flight courses within the circle are subject to be optimized . Figure 8 (b) shows the arriving flows around EWR, TEB, JFK and LGA in New York Metroplex. Obviously, arriving flows of different airports interlace with one another. Not only should the flights flying to the same airport be sequenced, but also the flights belonging to different flows be staggered in time. Therefore, the inbound traffic of metroplex airports should be sequenced as a whole. In this project, six metroplexes are chosen (see Table 2), which includes a subset of the major airports in the continental United States.

Table 2 Metroplex airports

Metroplex	Airport Code
New York	EWR, JFK, LGA, TEB
Texas	SAT, AUS, IAH, HOU
North California	SFO, SJC, OAK, SMF
South California	LAX, ONT, SAN
Washington DC	BWI, IAD, DCA
Chicago	ORD, MDW

The algorithm can schedule a whole day's traffic. But in real implementation, the planning time horizon is divided into several time windows, and then each window could be represented by an independent optimization problem. This is due to the fact that air traffic managers generally look into traffic of 4 or 6 hours ahead. In practical settings, it is difficult to predict the trajectory of an aircraft before its departure or long before its arrival. Therefore, dividing the whole day into 6 4-hour time windows is more close to the real operation. Furthermore, comparing the traffic by time makes the optimization easy to solve as each time window involves only a subset of arriving aircraft of a day. If an aircraft is delayed and pushed into the next time window, its schedule will be "frozen". But the optimization of the next time window must take its presence into account, that is, other flights simply check with it for potential conflicts. If there are predicted conflicts, the other flights are delayed.

4. ***Benefits and tradeoff analysis*** (January ~ April, 2011, completed):

The objective airports are 26 major airports plus the six metropolex airports. Basically, the selected airports contain 40 major airports which covers majority of the inbound traffic in the continental United States. Hence, this project evaluates CDA on a nationwide basis. For the 26 airports, the inbound traffic in each airport is sequenced independently. For the metroplex airports, the inter-flow interference is taken into account. The flight plans are provided by the ASDI data on August 24, 2005. All trajectories are tracked with a 1 minute interval. The proposed sequenced algorithm is applied and statistics are obtained based on the simulated conflict-free traffic.

(a) Delay

The conflict-free CDA is achieved at the expense of delaying a set of arriving aircraft. Table 3 presents the delay statistics of the 26 major airports and the six metroplexes. It can be concluded that flights flying CDA are more difficult to sequence by comparing the Total delay and Max delay. In most airports, CDA has higher value than Step-down in these two terms. Over all, CDA incurs 25% more total delay than Step-down. Meanwhile, the maximum delay ($\boldsymbol{L}$) for the individual aircraft also suggests that CDA leads to higher delay. This observation is consistent with previous claims. CDA does not lend itself to staggering aircraft in space. As a result, it needs higher delay to stagger aircraft in time.

Table 3 Delay generated by the sequencing algorithm

Airport	AC No.	CDA		Step-down	
		Max delay (min)	Total delay (min)	Max delay (min)	Total delay (min)
ATL	1524	25	1912	25	1293
BNA	347	6	121	5	89
BOS	650	7	519	6	340
CLE	367	7	153	5	138
CLT	824	13	1087	9	827
CVG	802	12	1181	10	936
DEN	908	7	705	7	419
DFW	1168	7	1096	7	912
DTW	800	8	647	7	602
FLL	399	6	100	5	107
IND	349	6	104	5	93
LAS	717	12	520	15	311
MCI	285	6	38	5	36
MCO	510	8	338	6	232
MEM	674	23	1100	13	724
MIA	473	11	331	9	218
MSP	828	13	624	10	474
PDX	418	10	269	15	295
PHL	859	9	606	8	468
PHX	832	9	615	6	476
PIT	374	6	208	5	136
RDU	374	6	160	6	147
SEA	583	6	178	5	195
SLC	646	12	455	8	227
STL	462	6	139	5	130

TPA	346	6	114	7	134
New York Metro.	2236	28	1686	28	1810
Texas Metro.	1549	9	1324	13	1309
North Cal. Metro.	1279	13	1067	12	818
South Cal. Metro.	1405	25	1847	27	2089
Washington DC Metro.	1724	27	1984	14	1626
Chicago Metro.	2019	19	5152	20	3496
Total	**26731**	**-**	**26380**	**-**	**21107**

(b) Benefits and tradeoff

Delay generated by the sequencing algorithm can be absorbed by either ground delay or airborne delay. From a perspective of fuel economy, ground holding saves more fuel as there is no unnecessary fuel burn for airborne delay. However, ground holding program postpones departures at the origin airports. Delayed aircraft may not be granted departure time slots at a later time during busy hours so that longer delay might be enforced. In contrast, airborne delay is more flexible, but more expensive as well. Figure 9 shows the delay distribution in New York Metroplex airports. It can be seen that most of the delays imposed on the arriving flights are less than 5 minutes in either CDA or Step-down. Thus the delays are easy to absorb by airborne delay. Both delay strategies are simulated and compared in terms of fuel consumption. The results are summarized in Table 4.

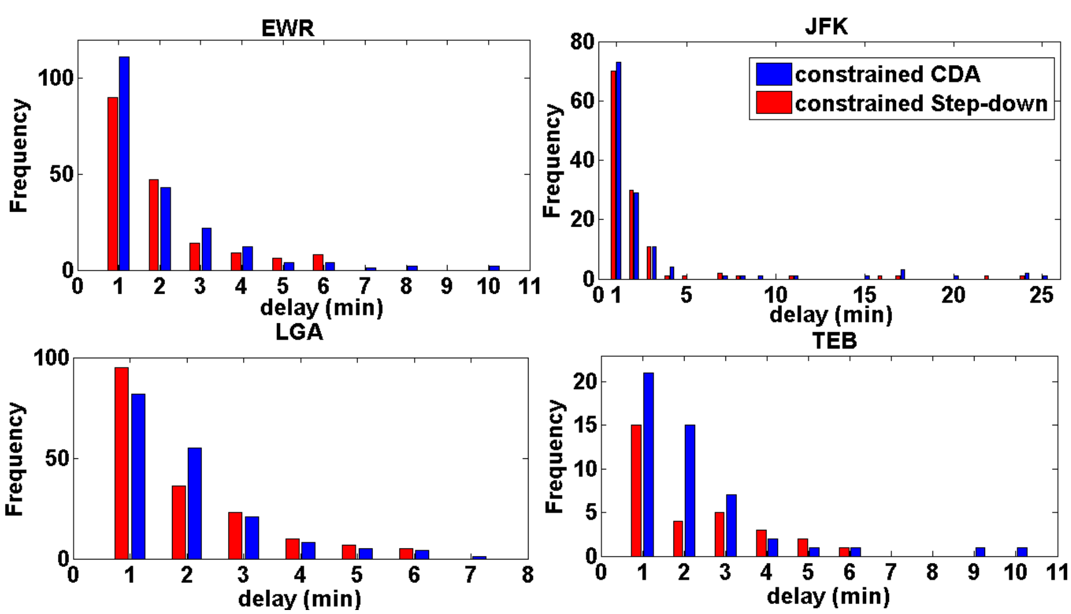


Figure 9 Delay distribution in the New York Metroplex airports

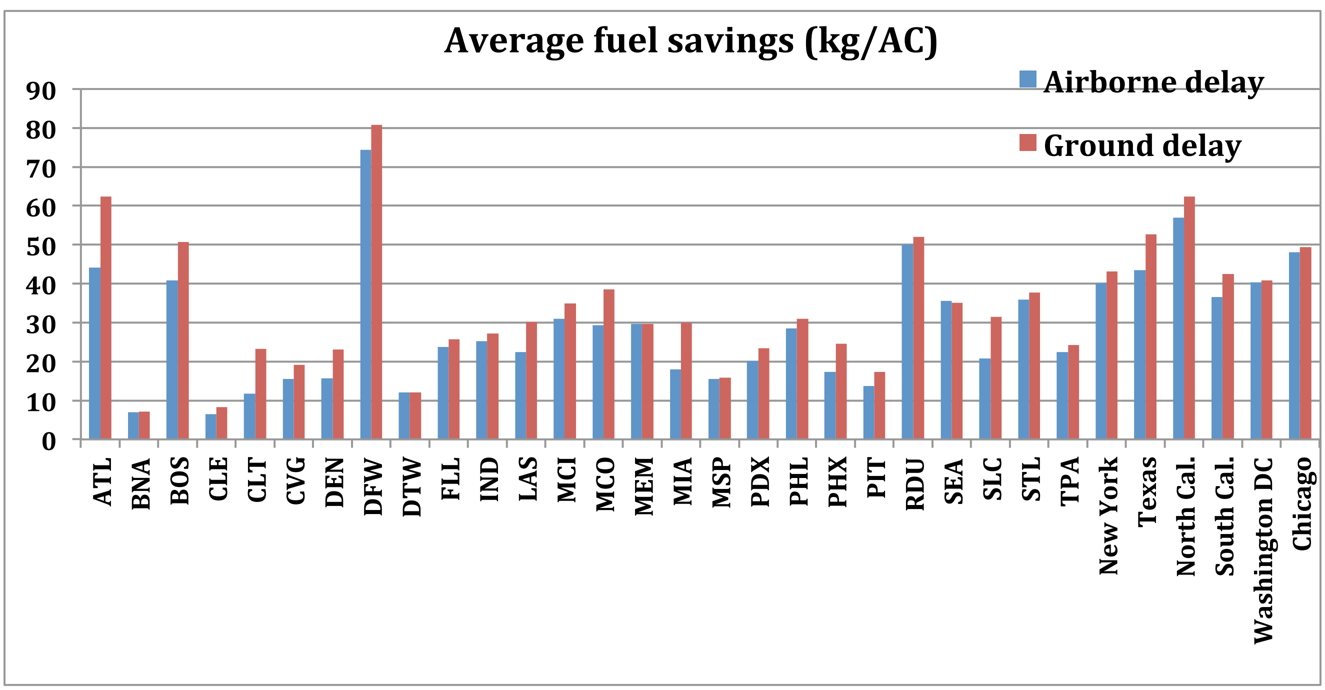
The fuel saving of an airport is the fuel consumption difference between the conflict-free Step-down and the conflict-free CDA. From Table 4, it is observed that Ground delay leads to higher total fuel saving as it avoids the extra fuel consumption due to delay. The saving is proportional to the aircraft number. The busier the airport, the higher the total savings could be. The flight time saving is the flight time difference between the conflict-free Step-down and the conflict-free CDA in the terminal airspace where delay is not counted as it is imposed outside the terminal airspace. The flight time saving is a consequence of avoiding low altitude level-off. CDA keeps the aircraft cruising at high altitude as long as possible. The aircraft stay in high speed settings for longer.

Table 4 Total fuel and flight time savings by airports

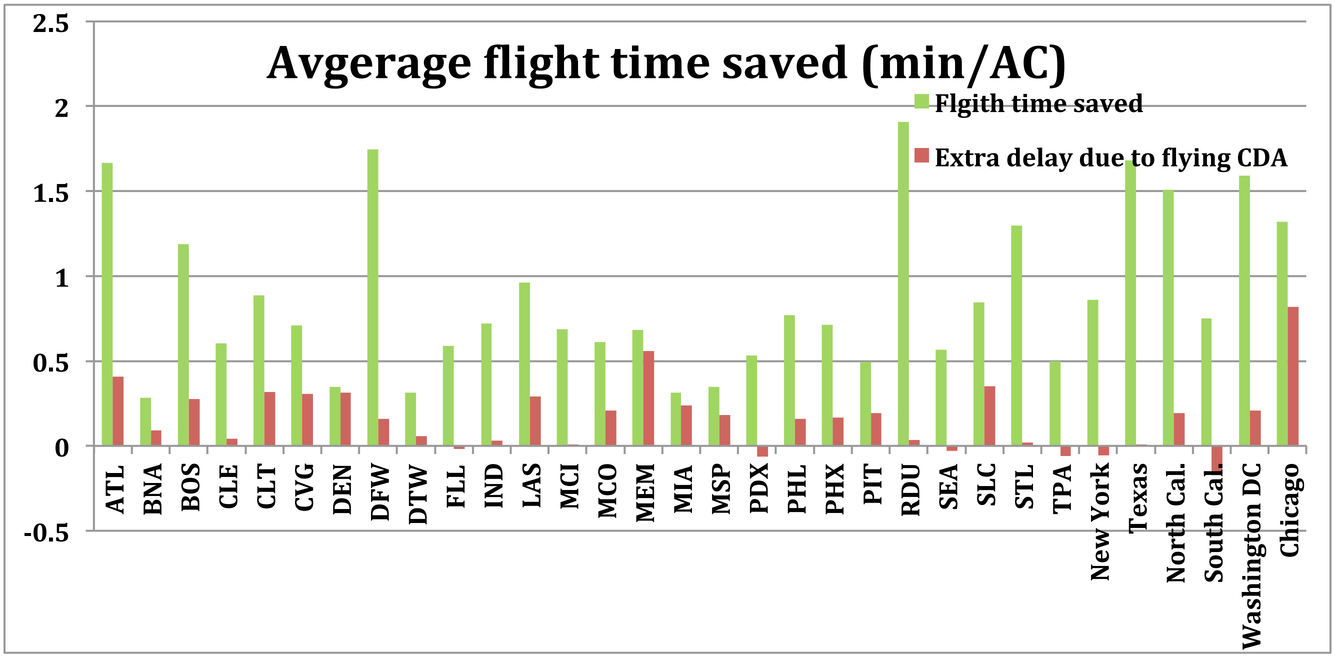
Airport	AC No.	Fuel saved/kg (Airborne delay)	Fuel saved/kg (Ground delay)	Flight Time saved /min
ATL	1524	67370	95160	2539
BNA	347	2424	2454	98
BOS	650	26580	32912	773
CLE	367	2382	3036	222
CLT	824	9610	19220	729
CVG	802	12420	15393	570
DEN	908	14300	20955	317
DFW	1168	86900	94286	2038
DTW	800	9640	9654	250
FLL	399	10680	10275	235
IND	349	8810	9493	252
LAS	717	16100	21610	689
MCI	285	8826	9941	196
MCO	510	14940	19624	312
MEM	674	19970	20029	460
MIA	473	8500	14219	148
MSP	828	12890	13077	288
PDX	418	8420	7251	223
PHL	859	24560	26549	662
PHX	832	14380	20455	594
PIT	374	5139	6479	185
RDU	374	18714	19468	713
SEA	583	20790	20441	329
SLC	646	13430	20344	546
STL	462	16580	17423	599
TPA	346	8790	8388	173

New York Metro.	2236	9520	96540	1922.96
Texas Metro.	1549	67280	81524	2602.32
North Cal. Metro.	1279	72940	79853	1931.29
South Cal. Metro.	1405	51360	59610	1053.75
Washington DC Metro.	1724	69690	70300	2741.16
Chicago Metro.	2019	97190	99650	2665.08
Total	**26731**	**831125**	**1045613**	**27056.56**
Average		**31.09**	**39.11**	**1.01**

Figure 10 shows the average savings. In Figure 10 (a), it can be seen that the fuel savings are between 20 kg/AC and 60 kg/AC. Table 4 shows that CDA saves 31.09~39.11 kg/AC in average. IATA has reported 50~200 kg fuel savings per flight by flying CDA. The estimation from the simulation is within the confinement. It worth noting that large airports, such as ATL, DFW, and Chicago Metroplex, have higher average fuel saving. This is due to the percentage of aircraft type in the total arriving aircraft, which will be analyzed later. In Figure 10 (b), the flight time saving is between 0.5 min/AC and 1.5 min/AC. The mean value is 1.01 min/AC. The extra delay per flight due to flying CDA is also presented. It is the difference between the average delay of CDA and the average delay of Step-down. The extra delay can be deemed as the trade-off of replacing Step-down with CDA. Compared to the average flight time saved, such trade-off is minor. Therefore, CDA is still beneficial. Comparing Figure 10 (b) with Figure 10 (a), one may find that the profile of the bars are similar, that is, the more flight time is saved, the more fuel is saved. This is consistent to the common sense.



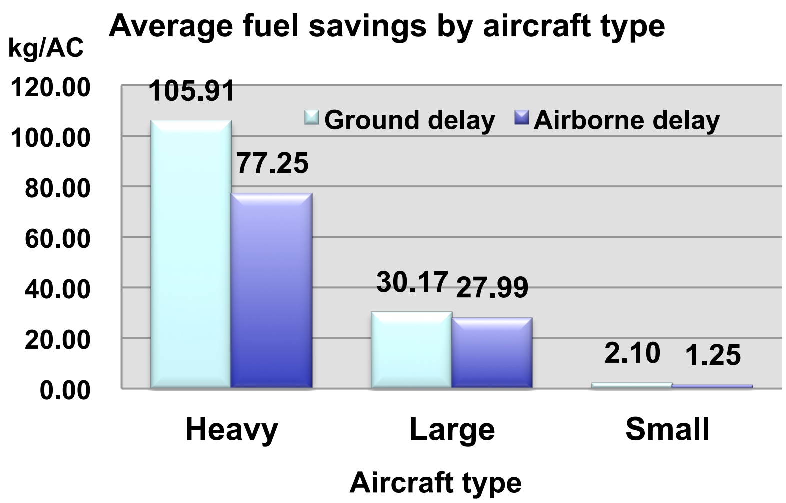
a) Average fuel savings



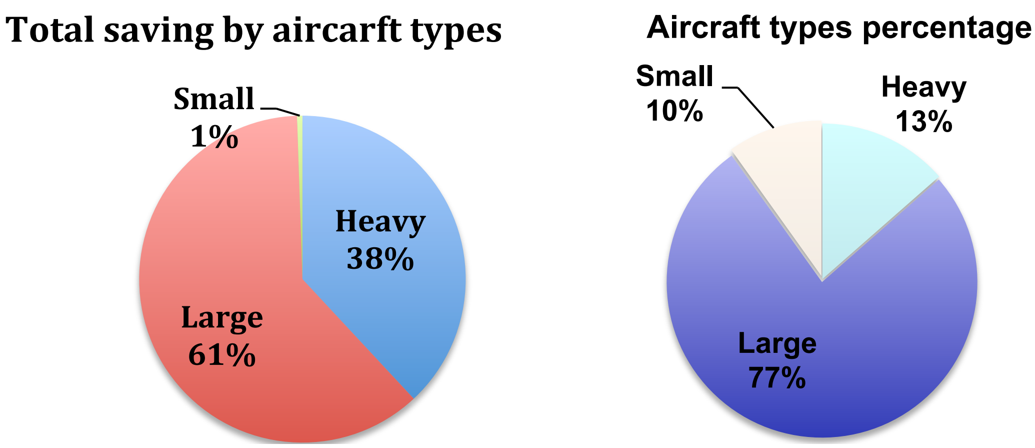
b) Average flight time savings

Figure 10 Average saving statistics

Figure 11 presents the average fuel savings as a function of aircraft type, which is obtained from the national statistics. There are over one hundred different aircraft types landing in the US in a whole day, it is trivial to check the fuel savings in terms of specific aircraft type. We categorize the aircraft by their sizes which are defined by FAA. It can be seen that the larger the aircraft size is, the more fuel the aircraft saves. This is due to the higher fuel flow rate of larger aircraft. Heavy aircraft consumes fuels more than twice of Large aircraft does. However, Large aircraft accounts for 77% of the total arriving aircrafts and contribute to 61% of the total fuel saving. Therefore, the average fuel savings of an airport is determined by two factors- the aircraft type and the corresponding percentage. Figure 12 exemplifies this speculation. JFK achieves an average fuel saving that is over ten times more than that of TEB. Observing the percentages of aircraft types, one may find that Large aircraft accounts for roughly the same percentage in both airports, but it is the Heavy aircraft that contributes to the huge difference. Heavy aircraft accounts for 43% of the total arriving aircraft in JFK while Small aircraft accounts for 53% of the total arriving aircraft in TEB. Therefore, applying CDA to the big airports will receive significant benefits.



a) Average fuel saving versus aircraft type



b) Percentage of aircraft type and corresponding contributions

Figure 11 Aircraft types

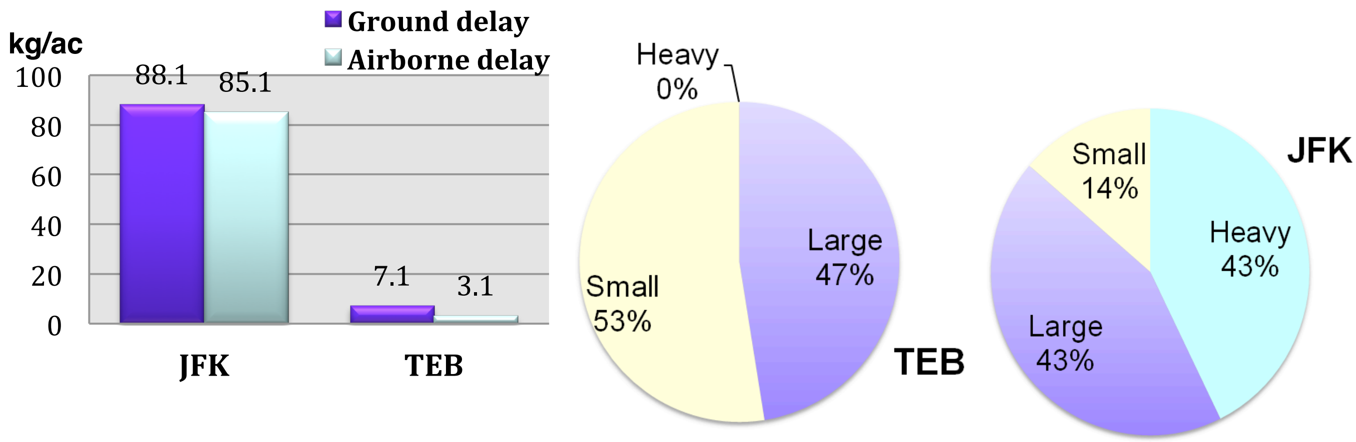


Figure 12 Fuel savings and aircraft type percentages

Major Accomplishments

This project concentrates on quantifying the benefits and trade-off of employing CDA in the normal air traffic condition. A sequencing algorithm is proposed targeting at achieving a conflict-free traffic for evaluation. In a simulation cycle involving 26 major airports and six metroplex airports, conflict-free CDA and conflict-free Step-down are both simulated. By analyzing the statistics results extracted from FACET, we can come to the following conclusions:

a) If current Step-down approach is replaced by CDA, there is great potential to decrease the fuel consumption and total flight time in the terminal airspace traffic. The benefits gained would be significant for major and metroplex airports given with large volume of inbound traffic.
b) The fuel savings has tight connection with the aircraft type. Heavy aircraft has the highest savings while Small aircraft has the lowest. Large aircraft contributes most to the total fuel saving while Small aircraft does the least. Mostof the arriving aircrafts in the objective airports are Large size.
c) As a trade-off, CDA inclines to increase the difficulty of sequencing the arriving flow. Because it has limited degree for the aircraft to be spaced compared to conventional Step-down approach. But at the same time, the drawback of employing CDA is to increase the delay for de-confliction purpose.
d) Constrain Position Shifting is effective in scheduling the arriving flows. It solves predicted conflicts without changing speed and flying direction, CDA profile is thereby preserved.

Although the simulation ignores some practical considerations, such as weather, wind, and many other factors, it provides the decision maker with a reasonable estimation of benefits and trade-off brought by CDA.

Publications/Presentation/Conferences

Cao, Y., Kotegawa, T., Sun, D., DeLaurentis, D., Post, J., "Evaluation of Continuous Descent Approach as a Standard Terminal Airspace Operation," 9th USA/Europe Air Traffic Management Research and Development Seminar. Berlin, Germany, June 14-17, 2011.

Cao, Y., Rathinam, S., Sun, D., "A Rescheduling Method for Conflict-free Continuous Descent Approach," AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, USA, Aug 8-10, 2011.

Awards
N/A.

Transition of Research Results
N/A.

Plans for Next Period
N/A