Evaluation of Continuous Descent Approach as a Standard Terminal Airspace Operation

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***Abstract*—This paper presents a simulation-based evaluation of Continuous Descent Approach (CDA) which is used as a standard terminal airspace operation at New York Metroplex airports. Initial simulations reveal that granting the freedom to arriving flights to plan the user-preferred continuous descent trajectories incurs conflicts. A scheduling method is proposed to strategically solve the conflict based on the 4-D trajectory concept. Initially, arriving flights plan their times of arrival and preferred descent trajectories without considering mutual interferences. Estimations of such 4-D trajectories are used to sequence the arrival flows. A Mixed Integer Linear Program is established to produce a conflict-free CDA while minimizing the total delay under separation constraints. Four scenarios, namely unconstrained step-down, constrained step-down, unconstrained CDA and constrained CDA, are simulated and statistically analyzed. The overarching goal of the research is to examine the feasibility of CDAs at the national level, in particular to provide a better estimate of the benefits and trade-off of the conflict-free CDAs.**

***Key words*—continuous descent approach, scheduling, 4-D trajectory.**

I. Introduction

International aviation is cited as a contributor that accounts for roughly 2% of manmade greenhouse gas emissions [1]. Efforts to reduce gas emission brought attention to the Continuous Descent Approach (CDA) as a method to reduce environmental impacts. The benefits of CDA have long been recognized and intensively studied. However, historical CDA research works have been focused on noise abatement, and the fuel burn savings that can be achieved by implementing CDA to the current operations are not well known

Efforts have been constantly taken to evaluate CDA implementations. European Commission initiated a program, known as Optimized Procedures and Techniques for Improvement of Approach and Landing (OPTIMAL) in 2004, in which CDA profiles and associated descent procedures are established [2]. Two major field tests were reported. The first was the Schiphol CDA trials in 2006 at Amsterdam, Netherland [3], [4]. The other was the Heathrow Airport practice in 2007 [5], [6]. In U.S., a program known as Partnership for AIR Transportation Noise and Emission Reduction (PARTNER), also designed detailed CDA models, and conducted field tests at Louisville International Airport (KY, U.S.) in 2002 and at Los Angeles International Airport in 2007 [7], [8]. Findings from these evaluations are consistent: CDA saves fuel, reduces noise and emission, and decreases the total flight time. However, it is also reported that CDA may decrease the airport throughput for poor predictability of descent trajectory. The vertical and time profiles for CDA require more space in the vectoring area. Air Traffic Controllers (ATC) have to block large chunks of airspace, which increases the landing interval from 1.8 minutes to 4 minutes on average as a result [9]. So far, CDA has only been tentatively practiced in selected airports during periods of low traffic density. In the Louisville airport trial, the designed procedures were only assigned to UPS aircraft and conducted during nighttime hours. In 2009, a trial at Atlanta airport only considered flights from Delta Air Lines and AirTran Airways. Similarly, in trails at London Metroplex airports (Luton, Stansted, Gatwick, and Heathrow), the reported benefits were based on statistics from nighttime operations only.

Due to the difficulty of testing CDAs in a high traffic environment in reality, simulation-based evaluations were conducted in which spacing and sequencing issues were taken into account. In [10], the simulated traffic involved around 2,800 flights at Atlanta airport using the simulation tool Total Airport and Airspace Model (TAAM) [11], where altitude and ground track restrictions were removed to allow aircraft to fly the optimal trajectories. It is reported that the number of loss of separation increases by 10%. In [12], simulations using a full day traffic data at Denver International Airport validated a method that is designed for solving conflicts between the arrival and departure traffic. But the descent trajectories preserve parts of the level-offs in order to stagger the arrival and departure flows at different altitudes. An analysis of ground automation impact on the CDA in a high density environment was presented in [13]. Merging and spacing commands were issued to the arriving traffic to enable a conflict-free CDA. However, this study did not carry out any trade-off analysis between fuel savings and operation throughput.

Our ongoing research examines CDA as a standard terminal airspace operation, providing an estimate of the benefits gained from the conflict-free CDAs. A simulation-based assessment is conducted based on the Future ATM Concept Evaluation Tool (FACET) [14]. The key contributions of this paper are:

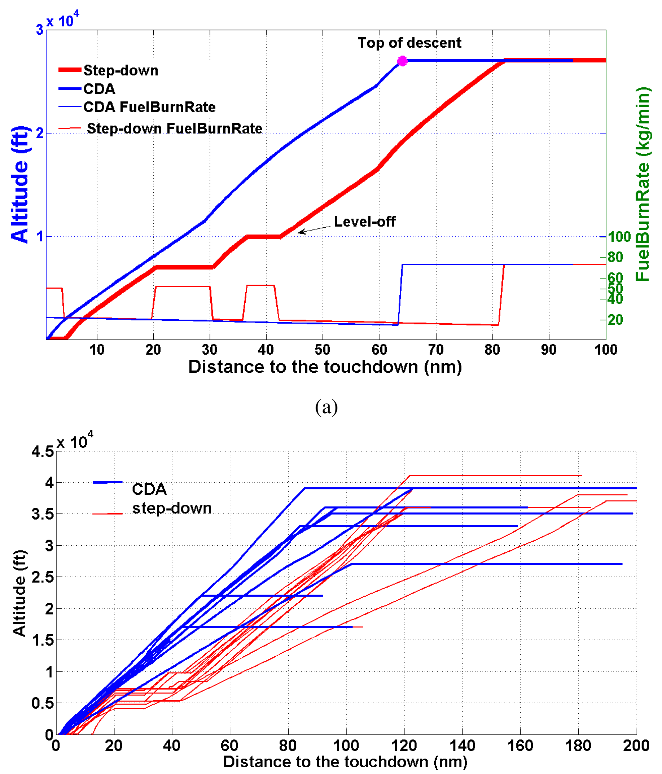
1) the development of a scheduling method that can achieves conflict-free CDAs in high density traffic envi-

ronment.

2) trade-off analysis between operation throughput, fuel and time savings with the conflict-free CDAs implemented at New York Metroplex airports.

The rest of this paper is organized as follows. Section II introduces the simulations based on FACET. Section III describes the scheduling algorithm for de-confliction purpose. Section IV presents the simulation results in which the scheduling algorithm validation is first shown followed by the analysis focusing on quantifying the benefits and the trade-off by employing CDA. Section V discusses the limitations in current CDA implementations. Conclusive remarks are provided in Section VI.

II. CDA IN FACET SIMULATION



(a)

(b)

Figure 1. **(a) Comparison of the simulated vertical profiles and speed profiles between CDA and step-down trajectories. (b) Samples of vertical profile simulated by FACET.**

FACET uses CDA profiles to establish the descending paths. Each arriving flight calculates the coordinates of the top of descent (TOD) according to the speed profile associated with a specific aircraft type. A sample is shown in Fig. 1(a). When reaching the TOD, a flight begins its descending. Its vertical speed and the fuel burn rate change upon the altitude at which it is flying. Overall, the vertical profile is a smooth glide slope with a 3-degree descent angle at the final approach.

To measure the benefits of the CDA, the step-down profiles are established as a baseline. Current descending trajectories involve several level-offs at low altitudes, depending on the traffic and local terrains around the destination airports. Generally, arriving flights may perform level-offs at altitudes between 3,000 ft and 10,000 ft and 30 to 50 nautical miles (nm) away from the touchdown. A step-down profile is simulated and shown in Fig. 1(a), which is calculated using the same ground track information in CDA. As can be seen, the flight begins the descending procedure earlier in step-down approach than in CDA. The step-down trajectory is similar to the CDA trajectory except for two level-offs at low altitudes. In step-down, the fuel burn rate increases when the flight levels off and uses high thrust. In contrast, the flight continuously descends keeping the fuel burn rate at a low level throughout the CDA. This low thrust setting is the main contributor in the overall fuel savings of the CDA.

Figure 1(b) presents some vertical profile samples obtained from FACET simulations. FACET has a built-in performance database specifying the speed profiles, commanded altitudes and other aircraft information associated with a specific aircraft type. Hence, different aircraft types result in different vertical profiles. In this study, only two level-offs are simulated which take place at altitudes between 3,000 ft and 10,000 ft in the step-down scenario. However, there are more level-offs in reality depending on surrounding traffic conditions, and the level-offs may happen at altitudes other than the prescribed range and last for different time periods as well. Moreover, the fuel burn rates during the level-offs vary against the altitudes. Hence, it is difficult to exactly estimate the fuel consumptions in real operations by simulation. It should be noted that the fuel burn statistics in this paper provide an estimation only.

FACET supports the 4-Dimensional (4-D) Trajectory concept, which has been drawing much attention. The 4-D trajectory approach is a concept targeted for enhancing the predictability of CDA profile [15]. The 4-D refers to 3-D position together with the time profile. Aircraft equipped with the Precision Area Navigation (PRNAV) system is able to fly a 4-D trajectory accurately within 0.1 NM and 5 seconds at all points on the pre-planned trajectory [10]. The concept strongly relies on most up-to-date advanced on-board Flight Management System (FMS) and reliable datalink between the ATCs and flights [16]. FACET is able to provide information of each aircraft on its waypoints with a preset trajectory update interval, which is 1 minute by default. The information includes 4-D trajectories, as well as fuel consumption, which enables statistical analysis in this study. Most importantly, the 4-D trajectory forms the basis for the proposed scheduling algorithm, which will be introduced in the next section.

One limitation in the FACET simulations is that the arrival rate of an airport is not under control. FACET delivers a flight according to the filed departure information extracted from the Aircraft Situation Displayed to Industry (ASDI) data [17], and navigates the aircraft according to the speed profile associated with a specific aircraft type. In the absence of control actions, the time of arrival of a flight is simply its departure time plus the airborne time. For this reason, the arrival orders at an airport may not reflect real situations. It is observed from the FACET simulation that the arrivals excessively exceed the arrival capacity of an airport, which is impossible in reality. However, this does not impede evaluation of the traffic. Quite to the contrary, this emulates a busy traffic environment which suitably serves the evaluation goal. The scheduling method proposed in this paper follows a “first scheduled, first-served” principle [18]. It allows flights to freely plan their landings first; and then it orders the arrivals based on the plans under separation constraints. The airport arrival capacity will also be taken into account when it sequences the inbound traffic, which will be shown later.

III. Scheduling Method

Benefits due to flying CDAs are expected to be evaluated in a full day horizon, and there should be no conflicts as well. In CDA, the idle thrust setting is the reason for fuel savings. But it decreases the controllability of an aircraft. Meanwhile, without level-offs, it is more difficult to stagger individual aircraft by altitude. Arriving flows have to share limited airspace in the terminal airspace. Thus there are higher probabilities of inferences between flights than current step-down descent, particularly in high density traffic environment. In air traffic management, there is a variety of de-confliction methods. When in conflict, aircraft generally take tactical maneuvers, such as changing ground speed, changing headings, changing vertical speed, or even a combined solution. However, given the nature of CDA, any of such strategies require extra thrust, tending to make the CDA aborted in mid-flight. Therefore, a more strategic solution is more preferred.

The following subsections focus on a scheduling method which strategically solves the predicted conflicts among the arriving flights. It is assumed that the flights are equipped with the 4-D capable FMSs and able to fly the planned 4-D trajectories.

A. Methodology

This study handles conflicts that are predicted in the terminal airspace only. A cylindrical region with a radius R centered around the airport is defined. The terminal airspace in this paper 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 subject to separation constraints. Figure 2 shows the snapshot of the terminal area bounded by a yellow circle at Newark Liberty International Airport (EWR). The blue lines are filed flight plans. There are several arriving fixes around EWR encompassed by the circle. Arriving flights begin descending within this circle. It is desirable not to issue controls to the arriving flights after they start the descents such that flights are able to follow the optimal descent paths according to the aircraft type performance settings. Therefore, control actions to de-conflict the traffic should be made before flights arrive at the boundary of the terminal airspace. An intuitive idea is to schedule each flight’s time of arrival at the boundary of terminal airspace.

The arriving aircraft set is denoted as $A = [A_1, A_2, \cdots, A_N]$. Initially, arriving flights independently plan their trajectories according to their flight plans without considering mutual interferences. Figure 3 illustrates the idea. For flight A_i and A_j, their 4-D trajectories within the

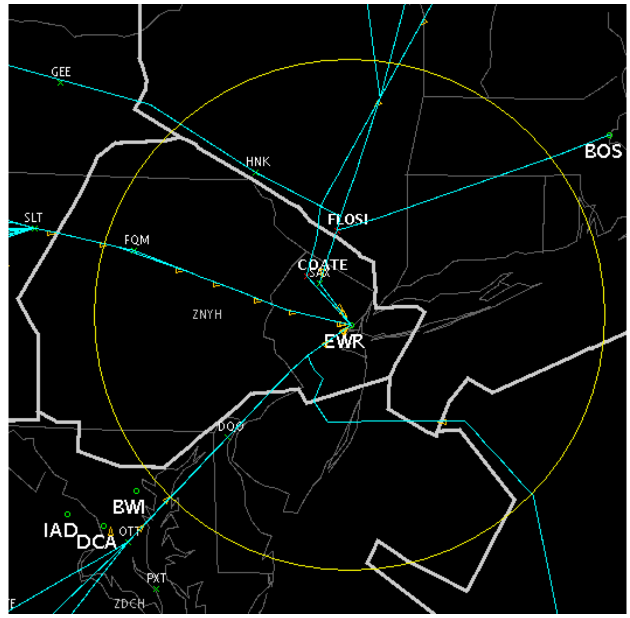


Figure 2. **Snapshot of the FACET simulation at EWR. Arriving aircraft intersect the final approach from three directions. Trajectories within the circle are subject to separation constraints.**

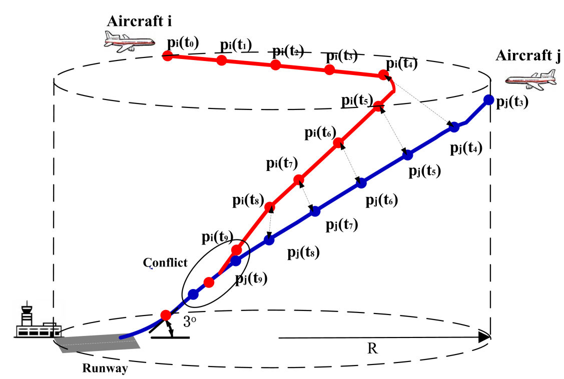


Figure 3. **Illustration of 4-D trajectory based conflict prediction. Two flights follow their planned continuous descent approaches within the terminal airspace and conflicts are predicted during descent.**

terminal airspace are of interest, which are denoted as lists of waypoints:

$$P_i(t_0^i, t_n^i) = [p_i(t_0^i, \varphi_0^i, \lambda_0^i, h_0^i), p_i(t_1^i, \varphi_1^i, \lambda_1^i, h_1^i), \cdots, p_i(t_n^i, \varphi_n^i, \lambda_n^i, h_n^i)],$$
$$P_j(t_0^j, t_n^j) = [p_j(t_0^j, \varphi_0^j, \lambda_0^j, h_0^j), p_i(t_1^j, \varphi_1^j, \lambda_1^j, h_1^j), \cdots, p_i(t_0^j, \varphi_0^j, \lambda_0^j, h_n^j)],$$

where $p_i(t_0^i, \varphi_0^i, \lambda_0^i, h_0^i)$ is the first waypoint where A_i arrives at the boundary of terminal airspace at time t_0^i, and $p_i(t_n^i, \varphi_n^i, \lambda_n^i, h_n^i)$ is the last waypoint where A_i finishes landing at time t_n^i. $\varphi^i, \lambda^i, h^i$ are latitude, longitude and altitude respectively. The waypoint list is, in fact, a temporal and spacial discretization of the trajectory with an interval ΔT. A_i and A_j are present in terminal airspace in time windows $[t_0^i, t_n^i]$ and $[t_0^j, t_m^j]$ respectively. If $[t_0^i, t_n^i]$ and $[t_0^j, t_m^j]$ intersect in some time window $[t_p, t_q] = [t_0^i, t_n^i] \cap [t_0^j, t_m^j]$, trajectories of these two flights must be checked for potential conflicts. A conflict detection function is defined:

$$CD(i,j,t_p,t_q)=\sum_{t=t_p}^{t_q} C(p_i(t,\varphi_t^i,\lambda_t^i,h_t^i),p_j(t,\varphi_t^j,\lambda_t^j,h_t^j)) \tag{1}$$

$$\begin{aligned} &C(p_i(t,\varphi_t^i,\lambda_t^i,h_t^i),p_j(t,\varphi_t^j,\lambda_t^j,h_t^j,)) \\ &=\begin{cases} 0 & if\ |h_t^i-h_t^j|\geq H \\ 1 & if\ (|h_t^i-h_t^j|<H)\ \&\&\ (d<D) \end{cases} \end{aligned} \tag{2}$$

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

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

$$\begin{aligned} P_i(t_0^i+\Delta t,t_n^i+\Delta t)=[&p_i(t_0^i+\Delta t,\varphi_0^i,\lambda_0^i,h_0^i),p_i(t_1^i+\\ &\Delta t,\varphi_1^i,\lambda_1^i,h_1^i),\cdots,p_i(t_n^i+\Delta t,\varphi_n^i,\lambda_n^i,h_n^i)] \end{aligned}$$

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., A_i will pass the original waypoints with a delay of Δt. Due to the delay, the intersection of time window is changed to $[t_p',t_q']$. If the trajectory of the aircraft is sufficiently shifted, then, one can ensure that $[t_p',t_q']=\emptyset$, 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 boundary. 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 cause additional conflicts with other aircraft. The objective is to determine the minimum delays needed to de-conflict the inbound traffic. Such problem can be formulated as a Mixed Integer Linear Program (MILP).

B. *Mixed Integer Linear Program Formulation*

Define a decision variable vector for each aircraft:

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

where w_k^i is a binary variable. w^i means there are L possible delay solutions assigned to A_i, each with a delay of $k\Delta T$. If A_i is assigned the k^{th} delay solution, $w_k^i=1$; other decision variables associated with 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. (5) is the weighted delay. c^i are the weights given consideration to the fairness among flights. It is subject to:

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

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

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

$$\textbf{then}\ \text{set: } w_{k_i}^i+w_{k_j}^j\leq 1, \tag{8}$$

$$i,j\in\{1,2,\cdots,N\}\qquad k_i,k_j\in\{0,1,\cdots,L\}$$

Eq. (6) means each flight can only be assigned one delay solution. Eq. (7) is the binary constraint. Eq. (8) 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. (8) 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 computationally very difficult to solve. 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 one, 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 consider 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 [20], 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 time of landing of 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 times of arrival $t_{landing}^i$ are sorted in a non-decreasing order using the *Bubble sort* algorithm [21]. And then successive arrivals are checked for the minimum in-trail separation. Suppose that A^j lands next to A^i:

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

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 I.

TABLE I
SCHEDULING 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 $([t_p, t_q] \neq \emptyset$ && $CD(i, j, t_p, t_q) > 0)$
$w^i_{k_i} + w^j_{k_j} \leq 1, \quad i, j \in \{1, 2, \cdots, N\}$
end if
} ***while***(infeasible solution)

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

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 $\{t^i_{landing}\}, \quad i \in \{1, 2, \cdots, N\}$

IV. SIMULATION

This section presents the simulation results. Figure 4 shows the flowchart of the simulation, which consists of two parts, the traffic simulation based on FACET and the optimization based on CPLEX [19]. Flight plans extracted from the ASDI data are fed into FACET. FACET is run on *simulation mode*, which means that FACET navigates the aircraft according to the filed flight plans, aircraft types and the built-in aircraft performance database. As a result, the simulated 4-D trajectories are not completely identical with the actual trajectories. However, such simulation creates an ideal "conflict" environment for algorithm validation purpose since there are considerable loss of separation when aircraft are navigated without considering mutual interferences. In the actual flight records, these aircraft are well spaced by the ATCs. The simulation also emulates the situation in which the aircraft are granted the freedom to fly user-preferred descent trajectories. The simulated 4-D trajectories can be obtained by the APIs provided by FACET, and serves as the input to the scheduling algorithm. The MILP is coded in C++ and solved using CPLEX. When an optimal delay solution is obtained, another simulation is run where aircraft follow their flight plan routes with delay received. FACET has a built-in conflict detection module, which can be used to validate the algorithm.

A full day terminal airspace operations at the New York Center Metroplex airports (EWR, LGA, JFK, TEB) are simulated. The selected airports are ideal for evaluation as they have high daily throughput. Four scenarios are implemented with the ASDI data of the same date (March 1, 2005):

1) Simulation with unconstrained step-down (without scheduling);
2) Simulation with constrained step-down (with scheduling);
3) Simulation with unconstrained CDA;
4) Simulation with constrained CDA.

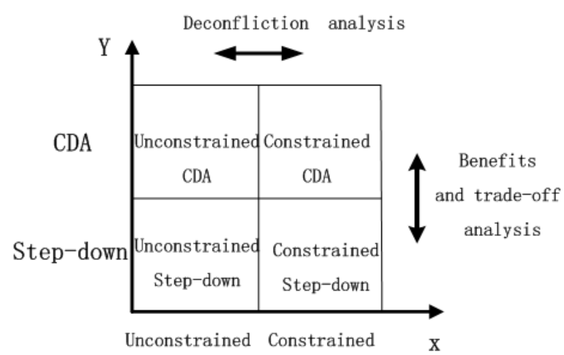


Figure 5. **Simulation matrix and comparison direction**

Figure 5 shows the simulation matrix. Basically, each descent approach has a constrained version and an unconstrained version. Comparing the simulations in different directions helps to evaluate the benefits as well as the trade-off of the conflict-free CDA. The following subsections present analyses focusing on three aspects.

1) Conflict resolution. This is done by comparing the constrained version with the unconstrained version of a descent approach in terms of elimination of conflicts.
2) Benefits analysis. This is done by comparing the constrained CDA with the constrained step-down in terms of fuel savings and flight time.
3) Trade-off analysis. In constrained CDA, different delay strategies to absorb the assigned delay are evaluated.

A. *Conflict resolution*

It is assumed that the traffic flows to the four airports do not interfere with each other. Hence each airport is treated independently. R is set to be 180 nm to ensure that the model covers the majority of descents. Initially, the weights c^i are set to be 1, meaning there is no priorities established to the arriving flights, and the objective function amounts to the total delays. Table II shows the results obtained from the simulations. In this study, the number of conflicts is counted in a way such that if two flights are in conflict for 5 minutes, the conflict count increases by five. From the third and sixth column in Table II, it is observed that conflicts occur frequently

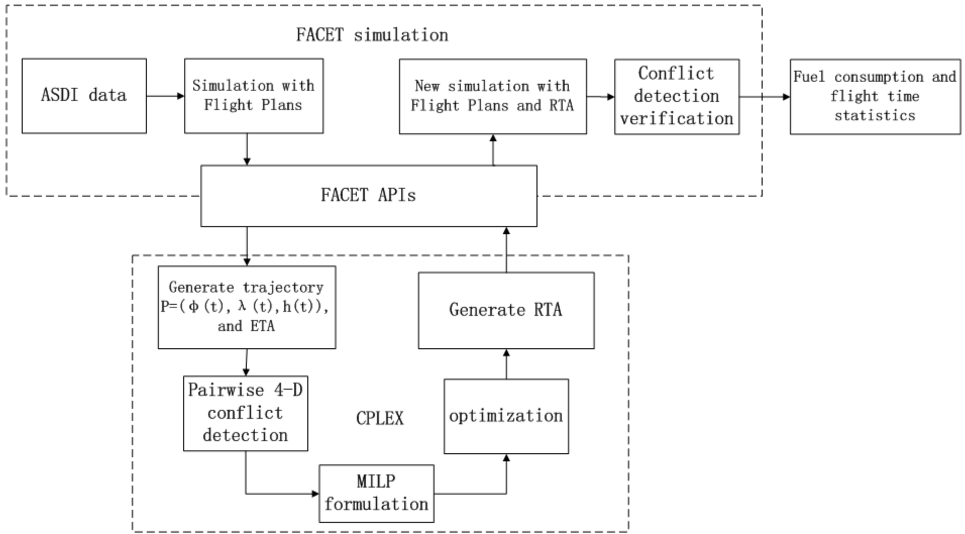


Figure 4. **Simulation flowchart.**

in both unconstrained CDAs and unconstrained step-down where flights enter the terminal airspace without control. In the constrained scenarios, all conflicts are successfully resolved with the scheduling method.

The fourth and seventh column show the total delay needed to resolve the conflicts, and the fifth and eighth column show the maximum delay assigned to an individual flight. It can be seen that the step-down has a higher conflict count than CDA. However, it requires lower delay assignment to resolve the conflicts. The maximum delay assigned to individual flight is also lower in step-down scenario. This indicates that it is easier to de-conflict the inbound traffic by staggering aircraft at different altitudes when they level off.

TABLE II
OPTIMIZATION RESULTS

Airport	No. of Landings	CDA			Step-down		
		Conflict count	Total delay (min)	max. indiv. delay (min)	Conflict count	Total delay (min)	max. indivi. delay (min)
EWR	720	736	436	11	799	478	11
JFK	587	533	405	28	592	203	28
LGA	670	534	343	11	732	435	5
TEB	267	111	118	11	129	85	6
Total	2244	1914	1302	-	2252	1201	-

Among the four airports, EWR is the busiest one as it has the most landings, and the highest conflict count suggests that the traffic density is also high. JFK has less landings and lower conflict count. However, the total delays that EWR and JFK receive are quite similar. The maximum delay assigned to an individual flight at JFK is even higher than that of EWR in both constrained CDA and constrained step-down. On the other hand, LGA has a close landing count as EWR, but its conflict count and total delays are lower than that of EWR. This indicates that the number of landings is not the determinant factor that affects the ease of de-confliction. Figure 6 shows the arrival rates of the four airports in CDA. The minimum in-trail separation constraint ensures the arrival rates do not exceed the benchmark rates. This constraint incurs some delays which are not counted in this paper. Since those delays are not a consequence of CDA but rather due to lack of terminal control which is available in reality. From Fig. 6, 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 must be delayed to enter 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 shows the distributions of the delay assignments. The majority of the flights receive delays that are no more than 5 minutes in both CDA and step-down scenarios. Therefore, the influence of the scheduling method on the total flight time is minor.

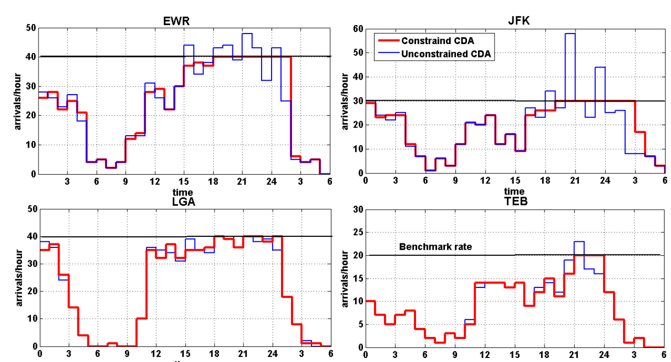


Figure 6. **Comparison of the arrival rates at the airports**

B. Benefits analysis

There are two advantages by flying CDAs, namely the fuel savings and the reduction of flight time in the descent phase. Fuel savings are calculated by taking the difference

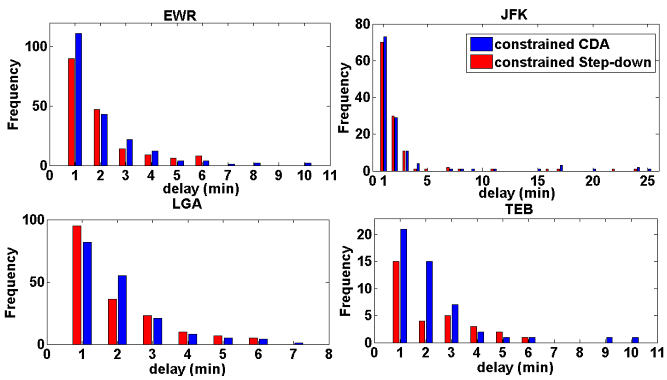


Figure 7. **Delay distributions at the four airports**

of the fuel consumptions between the CDAs and the step-down approaches, and the fuel consumption only counts the portion that are burned in the terminal airspace. Likewise, the flight time saving is the flight time difference between the constrained CDAs and the constrained step-downs in the terminal airspace. Since the constrained traffic within the terminal airspace of a descent approach is almost the same as its unconstrained version, their fuel consumption and flight time statistics within the terminal airspace are almost equivalent. Therefore, it makes no significant difference in which metric should be used to calculate the benefits. In the following statistical analyses, the constrained CDAs are used to compared with the constrained step-down in terms of the fuel savings and flight time reduction. Table III presents the savings in the terminal airspace. The average savings are shown in Figure 8.

TABLE III
FUEL AND FLIGHT TIME SAVINGS IN THE TERMINAL AIRSPACE

Airport	No.of Landings	Fuel saved (tonne)	Flight time saved (min)
EWR	720	24.48	599
JFK	587	74.76	872
LGA	670	24.57	663
TEB	267	1.9	250
Total	2244	125.71	2384

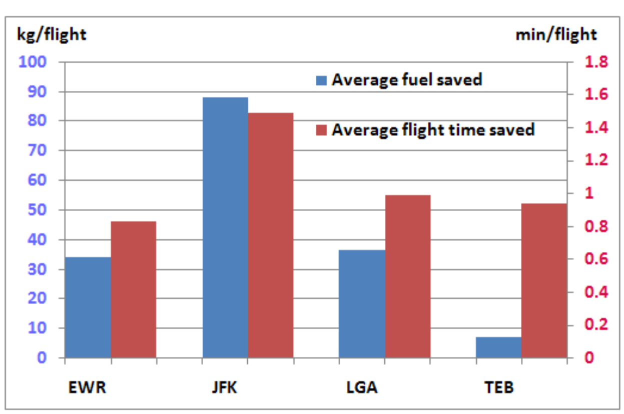


Figure 8. **Average fuel and flight time saved at the four airports.**

The fuel savings differ at the four airports. JFK has the most promising savings while TEB has the least. Results in Fig. 8 suggest that the average fuel savings of JFK is approximately three times as that of the EWR, and over twice as that of LGA. Figure 8 also shows that JFK has higher flight time saving than the other three airports. The aircraft types partially account for this observation. Revisiting Fig. 1, one may find that the vertical profile samples are quite different due to aircraft types. Each aircraft type has its own performance setting. The fuel burn rate is one of the factors contributing to the fuel savings. For example, a heavy aircraft with a high fuel burn rate can save more fuel than a small aircraft with lower fuel burn rate using CDA, especially when the flight times for the level-offs are approximately the same. If majority of flights landing at an airport are aircraft types that can save more fuel via CDA, it is entirely possible that the airport can achieve higher fuel savings. Figure 9 shows the contributions of fuel savings by different aircraft types at JFK and TEB respectively. It is observed that the main aircraft types contributing most to the fuel savings are heavy aircraft at JFK. In contrast, flights landing at TEB are largely medium size or small aircraft (see Table III for aircraft type definition). Hence, it is now clear why there are significant fuel savings differences between airports.

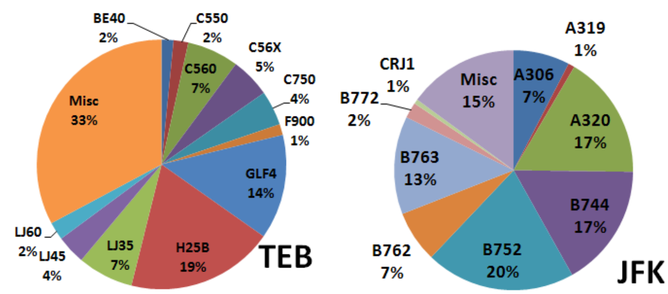


Figure 9. **Contributions of fuel savings by different aircraft types**

The 125.71 tonnes fuel saving counts the fuel burned in the terminal airspace only. It is essentially a direct consequence of using CDA. However, conflict-free CDAs incur extra cost since delay for de-confliction purpose would introduce extra fuel consumption. If the delay is in the form of airborne delay, the overall fuel savings would decrease, which are presented in Table V. The fuel savings are calculated by taking the fuel consumption difference between the constrained CDAs and the constrained step-downs over all flight legs of the trajectories. The overall fuel savings decrease by 20.96% due to delay control.

TABLE IV
TOTAL FUEL AND FLIGHT TIME SAVINGS OVER ALL FLIGHT LEGS

Airport	No.of Landings	Total fuel saved (tonne)	Decrease (%)
EWR	720	20.87	14.75%
JFK	587	49.95	33.19%
LGA	670	27.7	-12.74%
TEB	267	0.84	55.79%
Total	2244	99.36	20.96%

C. Trade-off analysis

Previous subsections has demonstrated the benefits of CDA by comparing it with step-down. This subsection examines the trade-off for introducing the scheduling method into CDA implementation.

Although the scheduling method successfully solves the conflicts, it can result in an increased number of delays. Previous analysis has shown that many delays assigned are less than 5 minutes. Compared to the total flight time of an aircraft, this level of delay is not significant. However, they do entail extra fuel consumption which decreases the benefits. The extra fuel consumption could be significant if an heavy aircraft receives delay. There are two alternatives to absorb delays. One is holding a flight on the ground; the other is delaying a flight while it is airborne. Ground holding is more preferred for safety and cost efficiency. However, if the delay is small, there is generally no need to issue ground holdings. Airborne flights can absorb the delay by changing airspeed. Only for flights receiving a great amount of delays, ground delay may save significant amount of fuel. However, ground delay program puts challenges on the origin airports, which have to accommodate the delayed flights as the departure slots become limited during the peak hours. The following paragraphs discuss both delay strategies.

1) Ground holding: suppose all the delays are in the form of ground holding delay. A delayed aircraft is hold on the ground. In this case, there is no extra fuel consumption.

2) Airborne delay: suppose all the delays are in the form of airborne delay. Flights have to change speed en route to absorb the delay, which causes extra fuel consumption. Table V shows the statistics, which cover all the landings at the four New York Metroplex airports. The statistics are classified by aircraft types. There were 110 aircraft types landing at the metroplex on that day. The first 15 aircraft types which contribute most to the fuel savings are listed. These aircraft types account for 54.9% of the total landings, and contribute to 78.9% of the total savings. The second column shows that the listed aircraft types are *Heavy* or *Large* in size (aircraft type definitions are according to FAA documents [22]). The sixth column shows that *Heavy* aircraft have higher fuel burn rate than *Large* aircraft. This observation is consistent with previous claim that the heavy aircraft saves more fuel. The last column shows the extra fuel consumption due to the airborne delay. Overall, the extra fuel consumption is 20.96% of the fuel savings achieved in the terminal airspace. Therefore, the fuel savings would decrease from 125.71 tonnes to 99.36 tonnes if airborne delay is issued.

Although the *Heavy* aircraft save a lot of fuel, the fifth column of Table V indicates that they also receive considerable amount of delays. It is an intuitive idea that decreasing the amount of delays assigned to the *Heavy* aircraft may reduce extra fuel consumption. This could be achieved by assigning different weights c^i to different aircraft types in optimizing the delay solution. In previous analyses, c^i is 1 for every aircraft type (unweighted scenario). Another simulation is run, in which the weights are assigned in the following way (weighted scenario):

$$c^i = \begin{cases} 1 & if\ aircraft\ type = Small \\ 2 & if\ aircraft\ type = Large \\ 3 & if\ aircraft\ type = Heavy \end{cases}$$

Such assignment establishes priorities to the arriving flights. The *Heavy* aircraft are less likely to be delayed in solving conflicts in CDAs. Table VI compared the weighted and unweighted scenarios. As can be seen, by weighing the objective function, the total delay increases by 75 minutes, but the extra fuel consumption decreases by around 3 tonnes. Figure 10 presents the detailed changes classified by aircraft types. From Fig. 10(a), the majority of the 15 aircraft types have their delay decreased, resulting in reduction of extra fuel consumption shown in Fig. 10(b). The delays needed for de-confliction are mostly transfered to the "Misc" (refers to miscellaneous aircraft types), most of which are *Large* or *Small* in size, causing its delay to be increased. However, the extra fuel consumption of "Misc" decreases instead of increasing. This may be due to the fact that the delays are transfered from the *Large* aircraft to the *Small* aircraft among the miscellaneous aircraft types. Less fuel is burned if most of the delayed flights are *Small* size.

Overall, changing the weights increases the fuel savings from 125.71 tonnes to 128.84 tonnes.

V. Discussion

It is noteworthy that experiment results should be interpreted in terms of research focus. Real air traffic control must take into account more practical considerations. For example, the air transportation system involves many commercial airlines. Under Collaborative Decision Making, equity is often addressed by fairly allocating delays to airlines rather than by maximizing fuel savings [18]. ATCs allocate a trunk of slots to airlines, and delegate the specific slot allocation to the airlines. In enrout traffic flow management, consideration is given to the traffic busyness. The Gini coefficient is used to measure the fairness of delay allocations amongst Centers [23]. In CDA

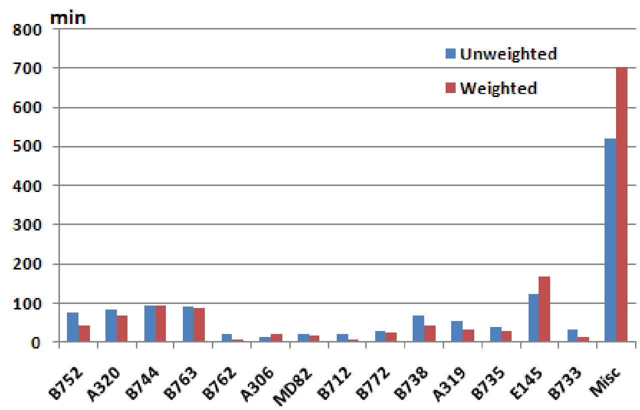
TABLE V
STATISTICS CLASSIFIED BY AIRCRAFT TYPES IN THE METROPLEX

Types	size	freq	fuel saved (tonne)	Delay (min)	Cruise fuel burnrate (kg/min)	Fuel burned for airborne delay (tonne)
B752	H[1]	166	25.35	79	49.6	2.13
A320	L[2]	145	12.04	84	46.5	2.68
B744	H	24	11.52	95	279	2.94
B763	H	34	9.97	92	99.5	0.31
B762	H	28	6.45	25	99.5	0.92
A306	H	24	5.7	13	45	0.59
MD82	L	40	4.8	20	55.6	0.81
B712	L	15	5.24	25	136.7	0.66
B772	H	12	4.66	27	99.5	0
B738	L	99	3.42	68	44.4	1.43
A319	L	73	2.71	55	46.5	1.14
B735	L	54	2.67	44	43.6	0.84
E145	L	214	2.41	123	12	1.2
B733	L	56	2.24	33	40.8	0.61
Misc	-	810	26.49	518	-	10.1
Total	-	1794	125.71	1302	-	26.35

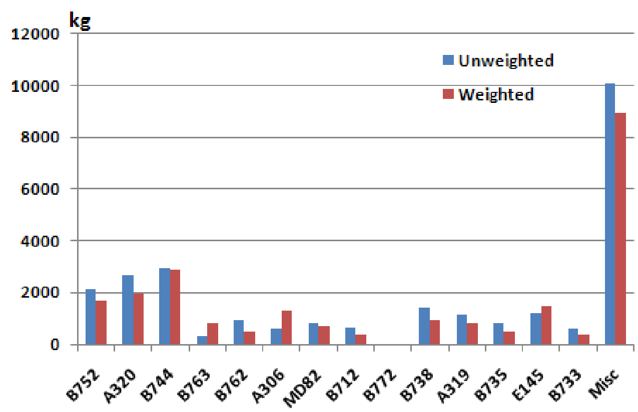
[1] Heavy
[2] Large

TABLE VI
COMPARISONS OF DELAY AND FUEL CONSUMPTION UNDER DIFFERENT WEIGHTS

Airport	Delay (min)		Fuel burn(tonne)	
	Unweighted	weighted	Unweighted	weighted
EWR	436	479	9.45	7.94
JFK	405	432	8.94	7.14
LGA	343	348	6.05	6.32
TEB	118	118	1.9	1.83
Total	1302	1377	26.35	23.225



(a)



(b)

Figure 10. **(a) Comparisons of total delays by major aircraft types between the weighted and the unweighted optimizations. (b) Comparisons of total fuel consumption for airborne delays by major aircraft types between the weighted and the unweighted optimizations**

study where fuel savings is one of the major objectives, it is appropriate to define equity in terms of minimization of fuel consumption. Hence, the fuel-oriented scheduling method gives an upper bound of fuel savings amongst many methods in arrival scheduling literature.

The framework presented in this paper does not consider uncertainties which are common in real air traffic management. The trajectory estimation is propagated through some pre-determined performance settings. The de-confliction decisions are collectively made and strictly executed, which are somewhat ideal. In reality, it is impossible to schedule all aircraft before they depart and ensure trajectory de-confliction. It is also impossible to require an aircraft to pass a position exactly at a required time. A time window is more reasonable.

The traffic optimization is applied to a whole day traffic, hence the total savings achieved is optimal in the sense of 24-hour planning horizon. However, ATCs generally look into traffic of 4 to 6 hours ahead. In order to adapt to real operations, the optimization should be performed with a shorter planning time horizon. Fig 11 compares the total delay calculated with 6-hour look-ahead time with that calculated with 24-hour look-ahead time. When the 24-hour optimization is divided into four consecutive 6-hour optimization, the amount of delay almost doubles for EWR, JFK, and LGA. It can be predicted that the fuel consumption due to airborne delay will increase,. The schedule is optimal only in the sense of 6-hour look-ahead time, but is shortsighted compared to the 24-hour optimization. Therefore, the aforementioned benefits are conditional upon the planning time horizon. The 24-hour optimization can be viewed as the upper bound of the optimality obtained from the proposed method.

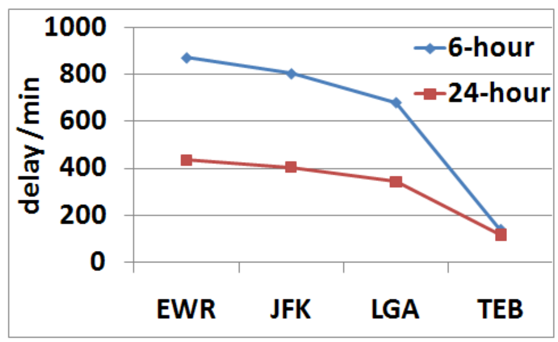


Figure 11. **Delay generated by different planning time horizons.**

VI. CONCLUSION

This paper has shown that the conflict-free continuous descent approach flown in high density traffic can be achieved based on the 4-D trajectory concept. The proposed scheduling algorithm is proved to be effective in strategically solving the conflicts occurring in the inbound traffic in a full day simulation of terminal airspace operations.

With the conflict-free CDA simulations, the benefits of CDA are quantified in comparison with the step-down approach. Simulation results show that 125.71 tonnes fuel and 2384 minutes flight time are saved as a direct consequence of CDA at the New York Center Metroplex airports. To achieve the conflict-free CDAs, the fuel savings decrease to 99.36 tonnes due to extra fuel consumption used for an airborne delay of 1285 minutes. Detailed analyses further reveals that the delays assigned to individual flights are largely short time periods, thus can be easily absorbed en route. Delay strategies are also evaluated. Airborne delay decreases the fuel savings. Moreover, by establishing landing priorities to the arriving flights by the aircraft types, the extra fuel consumption due to airborne delay can be reduced.

The proposed method provides a means to evaluate the conflict-free CDAs. Current evaluation is applied to metroplex airports only, which serves as a case study. The insights gained from current works help us to understand the benefits and trade-off. The overarching goal of this research is to evaluate CDA nationally. With current works, the evaluation can be easily expended to the national level in the near future.

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