Benefit and Tradeoff Analysis of Continuous Descent Approach in Normal Traffic Conditions

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ABSTRACT:

Continuous Descent Approach (CDA) has long been known as a fuel-efficient procedure due to elimination of low altitude level flights. However, many studies that examine the fuel savings fail to consider the increased separation uncertainties CDA brings about, which may cause extra fuel consumption for safe spacing. This study evaluates the fuel benefits of CDA at Atlanta Hartsfield-Jackson Airport taking into account the delays resulting from conflict resolutions. The fuel burn is estimated using a corrected Thrust Specific Fuel Consumption model that is designed specially for descent. The conflict-free CDAs are determined in such a way that the total arrival delays are minimized in each look-ahead time window. Resultant delays are converted to speed advisory or air holding commands executed in cruise phase to account for the impact of increased separations in CDAs. The fuel consumption of CDA is compared with that of real step-down trajectories extracted from radar track data. Results show that executing CDA does not guarantee fuel savings for individual arriving flights due to conflict avoidance, but the overall fuel consumption at the airport is reduced. The estimated fuel savings is less than that observed in the terminal airspace only, because deconfliction entails extra fuel consumption for delay absorption beyond the immediate terminal airspace.

INTRODUCTION

As public environmental awareness grows, the imperative to reduce greenhouse gas emissions must be addressed by all sectors, including aviation. International aviation is cited as a contributor that accounts for roughly 2% of manmade greenhouse gas emissions (**Error! Reference source not found.**). Decreasing fuel consumption and gas emission is inevitably a step toward the so-called green aviation. The U.S. Joint Planning and Development Office[1] has put forward an environmental goal in the NextGen blueprint (1), which lists Continuous Descent Approach (CDA) as a priority initiative. CDA has long been known as an environmentally beneficial procedure that results in noise abatement, fuel savings and emission reduction. In the last decade, CDA has been collaboratively studied by airlines, aviation companies, research organizations, and governmental authorities. The PARTNER (Partnership for AIR Transportation Noise and Emission Reduction) Center, sponsored by FAA, NASA, and Transport Canada are leading programs that assess CDA in the North America. Clarke et al. were among the first to investigate the benefits due to CDA at Louisville International Airport, and later at Los Angeles International Airport, and Atlanta International Airport between 2002 and 2006 (3-6). In Europe, counterpart programs involve Sourdine and OPTIMAL (Optimized Procedure and Techniques for the Improvement of Approach and Landing) (8,9). Several trial-based initiatives were published. An Advanced CDA procedure was defined and tested by Airbus aircraft between 2005 and 2006 at Schiphol airport (10,11). Trails are also conducted at Gatwick Airport in 2005 and at Heathrow Airport in 2007 respectively (12,13).

International Air Transportation Association (IATA) has reported 50~200 kg of fuel savings per flight by flying CDA (14), and EUROCONTROL estimated around 80,000 tonnes of fuel would be saved per annum in Europe airspace if CDA is flown (15). However, regardless of various promising environmental advantages, CDA is typically practiced during low-density traffic due to concerns over safety and airport throughput efficiency. As pointed out by Reynolds that the vertical path determination is passed to the fight crew while the Air Traffic Controllers (ATCs) retain lateral path determination and speed dimensions (16), the vertical and time profiles vary from aircraft to aircraft during the descent procedure, predictability and controllability of the arrivals consequently decrease. On the other hand, current FMS has an uncertainty in predicted longitudinal position that grows at an average rate of 0.2 nm per minute-look-ahead-time for level, un-accelerated flight (17). As a result, CDA entails larger separation in the vectoring area than conventional step-down approach. ATCs thus have to block large chunks of airspace, which eventually increases the landing interval from nominal 1.8 to 4 minutes (18). Hence, it is somewhat difficult to execute CDAs in high traffic. This can be confirmed by the fact that CDA is mainly executed at nighttime.

However, CDA's future is still promising and researchers continue to evaluate the CDA procedure analytically. Field testing, especially in busy or congested environments, is costly and may be hazardous when relying on the installed aircraft fleet's avionics and air traffic management tools. Simulation offers an efficient and safe method. Shresta et al. analyzed CDA benefits during daytime operations (19). The modeled CDA trajectories are obtained by changing the vertical profiles of radar track data. The fuel burn and speed brakes are computed based on the Base Aircraft Data (BADA). Experiments show that CDA decreases the fuel consumption by

[1] Joint Planning and Development Office was created by the United States Congress in 2003 to plan and coordinate the development of the Next Generation Air Transport System.

100~300 lbs per flight. But it is also found that CDA profiles cause potential interference with departure flows if the ground tracks are not changed. Shresta suggests that CDA be executed at certain altitude scope such that the aircraft can avoid conflicts by means of level flights. Such strategy eventually retains 15% of the savings. More recently, Robinson et al. (20) assessed CDA at a nationwide scope (35 OEP airports), where massive data processing work has been done to extract real-world trajectories (480,000 aircraft over 30 days). The authors estimated the upper bound and lower bound of the fuel savings using probabilistic distribution to describe the fuel efficiency of CDA. The wide spread of the fuel consumption data is observed due to aircraft weight class, weather days, and arrival routes.

Human-in-the-Loop Simulation reported by Johnson (21) found that air traffic controllers tend to provide additional buffer between aircraft flying CDA procedures in order to account for uncertainties in Top of Descent (TOD) points and speed profiles among different aircraft. As a result, there is an efficiency reduction in the arrival throughput. The spacing buffer actually causes increased flight time that must be absorbed during descent or in cruise phase, which partially offsets the fuel efficiency attributed to the optimized vertical profile. Therefore, the overall fuel efficiency of CDA should be lower than that observed in the confines of the terminal airspace. Most previous studies examine the fuel efficiency of CDA that results from elimination of level-flights only, but fail to take into account the influence of increased spacing that CDA brings about. This paper reports a simulation-based assessment of CDA fuel efficiency under ATC control at Atlanta International Airport (ATL). The CDA arrivals are subject to increased separation constraints. Delays calculated from the arrival scheduling algorithm are converted to speed change or air holding to account for the air traffic management practices. The CDA arrival traffic is simulated by the NASA Future ATM Concepts Evaluation Tool (FACET) (22) using radar track data as input, and the fuel burn is estimated using a high fidelity fuel model named corrected Thrust Fuel Specific Consumption (TFSC) model (24). The over-arching goal of this study is to evaluate the CDA in typical traffic conditions in order to provide a better estimation of the benefits of CDA in busy terminal environment.

EVALUATION SCHEME

Data Source

This research relies on high fidelity simulation. The baseline in this study is the radar track trajectories, which comes from FAA Performance Data Analysis and Reporting System (PDARS). The data contains flight information, such as 4-D trajectories, flight plans, arrival fix and ground speed. Fig. 1(a) shows the ground tracks of arriving aircraft into ATL throughout a full day’s operations for October 1, 2011. Subfigure B shows the Standard Terminal Arrival Routes (STARs) that transit the arriving aircraft from Air Route Traffic Control Center airspace to the TRACON airspace. Approximately 85% of arrivals follow STARs. ATL is chosen for this research for two reasons. First, ATL has wide open airspace. The inbound traffic enters the ATL terminal airspace through four corners. The arrival routes have a radial treelike structure. As a result, interactions between arrival flows are minimized, which make it easier for deconfliction modeling. Second, ATL is a hub airport that accommodates a large volume of traffic each day. A large sample size improves statistical significance of the data analysis. TABLE 1 lists the PDARS data used for CDA analysis.

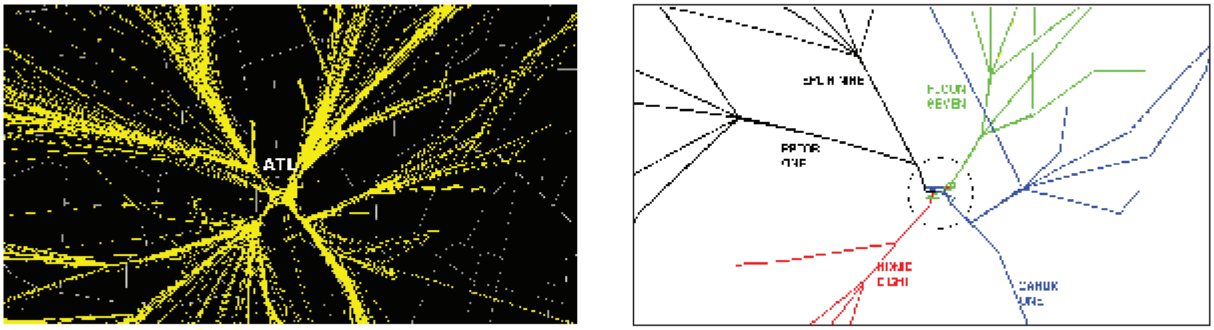


Figure 1 (a) Arrivals into ATL on 10/1/2011 (b) STARs into ATL TRACON.

Trajectories observed from the PDARS data mostly use conventional step-down descent. To create CDA traffic, aircraft type specific information as well as ground tracks are fed into FACET to synthesize CDA trajectories. FACET uses built-in aircraft performance data derived from BADA to propagate the vertical profile of a given aircraft type, which is typically a 3 degree glide path. The lateral path is determined by waypoints derived from either flight plans or a given geographic coordinates array. Figure 2 shows a sample step-down trajectory and the corresponding CDA version simulated by FACET. Their ground tracks are exactly the same, with only different vertical profiles. This is to ensure that the fuel consumption difference between CDA and the baseline is only a consequence of optimized vertical profiles and speed profile. The radar updates the aircraft position with an interval of around 1 minute. To obtain a finer resolution, the update interval is turned to 5 seconds in FACET SIMULATION mode. The simulated trajectory is a smooth glide path with delayed Time Of Descent (TOD) point.

TABLE 1 Daily arrival counts in PDARS data in October 2011

DATE	TOTAL ARR.	North West	South West	North East	South East	STARs* percentage
10/1/11	1089	300	184	305	121	83.56%
10/2/11	1234	329	227	359	108	82.90%
10/3/11	1320	364	239	387	152	86.52%
10/4/11	1257	343	236	369	148	87.19%
10/5/11	1251	353	236	360	130	86.25%
10/6/11	1296	361	247	372	122	85.03%
10/7/11	1340	381	264	383	134	86.72%
10/8/11	1112	308	231	290	110	84.44%
10/9/11	1235	340	234	343	124	84.29%
10/10/11	1306	360	255	379	152	87.75%
10/11/11	1296	353	279	358	151	88.04%
10/12/11	1259	361	241	352	106	84.19%
10/13/11	1293	369	235	372	161	87.94%
10/14/11	1353	385	254	369	142	85.00%

***STARs: Standard Terminal Arrival Routes**
Source: FAA________________________________.

Simulation for Conflict-free CDA traffic and Key Assumptions

CDA inbound traffic is obtained via FACET simulation. To set up the simulation, specific assumptions are made and note below and in the following discussion:

- The 4D trajectories extracted from PDARS data is real-world traffic that should have been deconflicted by ATCs, thus they are conflict-free in terms of FAA separation minima, i.e. 5 nautical miles (nm) for en route airspace and separation minima based upon wake vortex categories in the terminal airspace.
- Given an aircraft, the time stamp associated with the aircraft's first waypoint found in PDARS data corresponds to the takeoff time when the aircraft is created in the simulation. The time stamp associated with the aircraft's last waypoint in the simulation corresponds to the landing time. Delay defined in this study is the time shift from the landing time.
- Due to the lack of wind data, it is assumed that the true airspeed, V_{TAS}, is equal to the ground speed, which will be used in fuel estimation.

As CDA keeps the aircraft cruising for longer, and the speed profiles change as well, the arrival order and spacing change accordingly. The simulated traffic is no longer conflict-free. Conflict resolutions must be calculated to clear the loss of separations. Figure 3 depicts the data flows in the simulation. Radar track trajectories are assumed to be conflict-free, thus they can be processed directly by the corrected TSFC model to generate the baseline fuel consumption. For the conflict-free CDA scenario, the mission is done in two steps. The lower loop of Figure 3, Scenario 1, shows the first step. The ground tracks extracted from radar track trajectories are fed into FACET to generate the modeled CDA trajectories, which are also processed by the corrected TSFC model to obtain the fuel consumption without any ATC

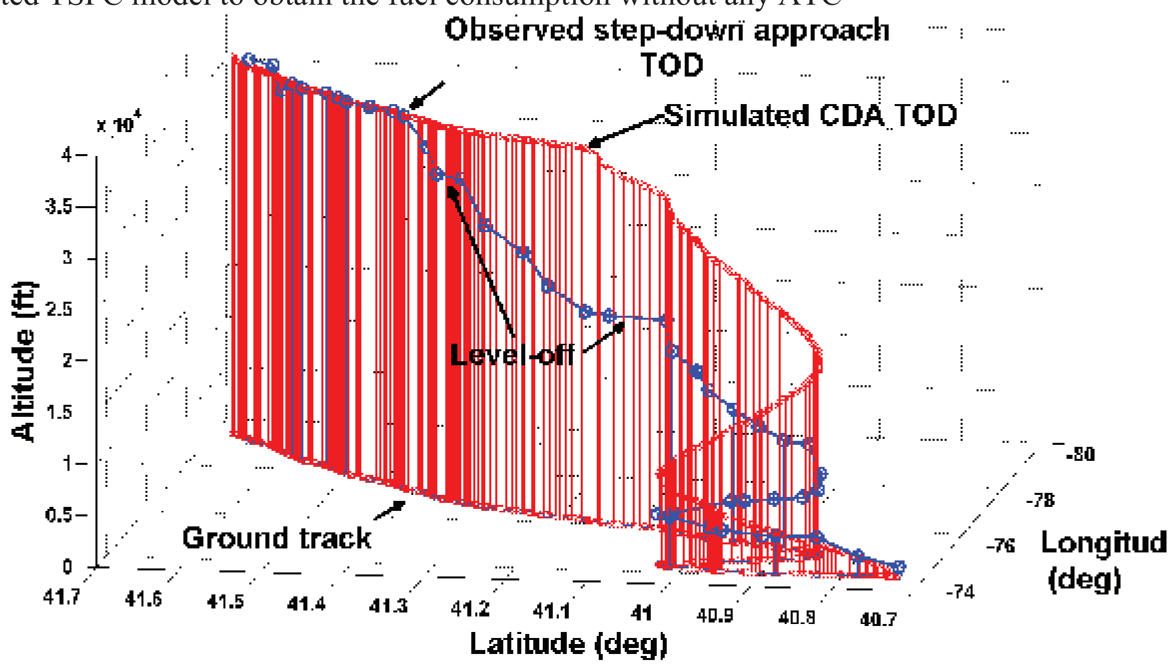


Figure 2 3D view of a B737 step-down trajectory extracted from radar track data and its simulated CDA version.

intervention. Then the modeled CDA traffic is deconflicted by a scheduling module that will be detailed later. An assignment of delays is obtained through this module, and is converted to speed advisory that will be sent to the second step. The upper loop of **Figure 3** shows the second step, Scenario 2. The FACET simulation runs with the speed advisory in addition to the ground tracks fed in the first step. Conflict-free CDA trajectories are obtained and processed by the corrected TSFC model to generate the fuel consumption under ATC invention. Finally, the fuel consumptions resulting from different scenarios are compared.

SIMULATION MODELS

The simulation contains three important components, which are described in this section.

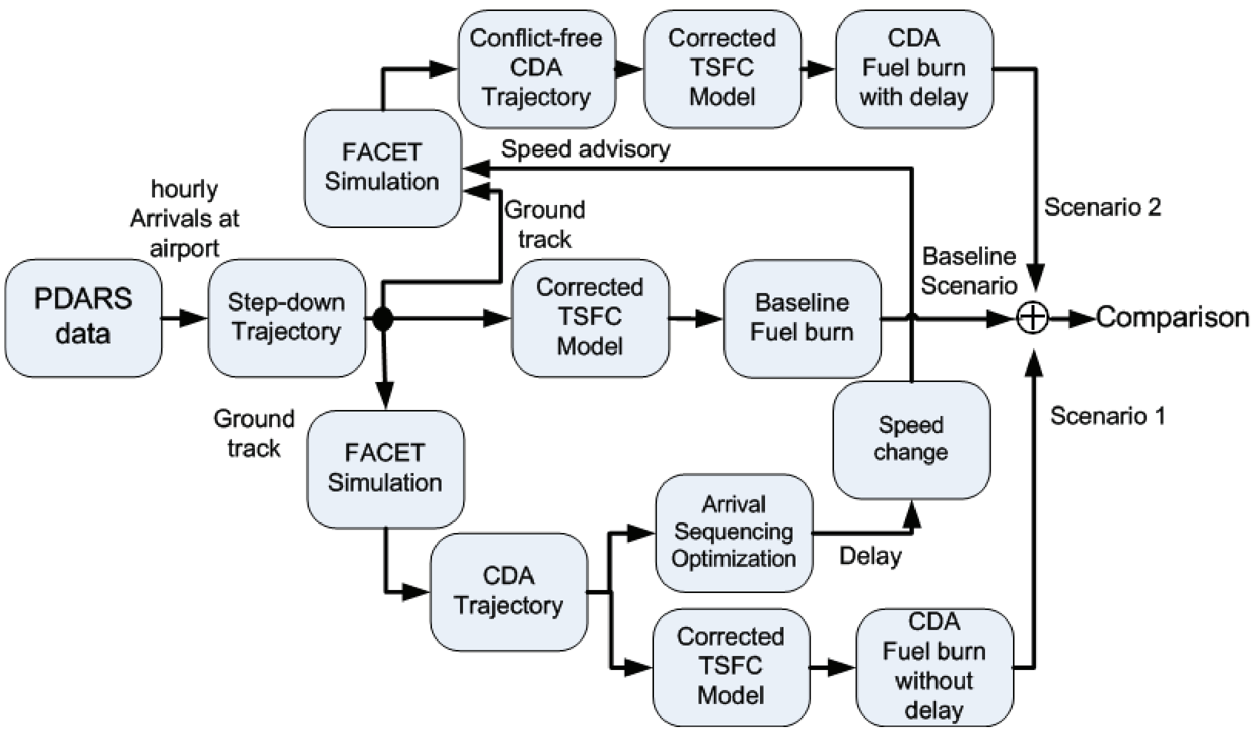


Figure 3 Simulation scheme.

Fuel Model

The fuel model is the backbone of this research. The precision of the fuel model is strongly related to the fidelity of the conclusion drawn from the results. A widely accepted model is the BADA Thrust Specific Fuel Consumption model (24), which is based on the Total Energy Model established as the aircraft dynamics. Research by Senzig et al (23) found that the original TSFC model was accurate for cruise mode, but it underestimated the fuel burn for climb and descent by -22.3%. Therefore, a corrected TSFC model is established by Senzig et al that provides approximately ±5% accuracy for climb and descent phase. However, this model is only calibrated under 16,000 feet above the mean sea level. Applying this model to altitudes above is actually extrapolating the model. Most of commercial transports cruise above 16,000 feet. To evaluate the fuel savings of CDA, it is necessary to compute the fuel flow rate backward from the runway threshold up to cruise altitude. As a result, there is a risk of introducing bias into the fuel burn estimation by using the corrected TSFC model. The most recent evaluation by the FAA John A. Volpe National Transportation System Center indicates that the difference between the actual and the corrected TSFC modeled fuel is bounded by 15% for the en route descent. Therefore, the corrected TSFC is used to provide the best approximation of the fuel burn in this study.

The corrected TSFC model is based on BADA model. To calculate the fuel flow rate during descent for jet (turboprop flight can be obtained via a similar derivation):

$$f_{nom} = \eta \times Thr$$

where Thr is the thrust, and η is the so-called thrust specific fuel consumption. The thrust is calculated via the Total Energy Model, which is a function of a set of aircraft type specific coefficients, aircraft configurations, altitude and true air speed. For brevity, interested readers are referred to BADA 3.9 user manual for detailed derivation of the thrust. The major improvement by the corrected TSFC is the estimation of η:

$$\eta = (\alpha + \beta_1 M + \beta_2 e^{-\beta_3 (F/\delta / F_0)})\sqrt{\theta}$$

where M is the Mach number, α, β_1, β_2 and β_3 are arrival TSFC constant coefficients associated with a particular aircraft type. θ is the temperature ratio at altitude over the sea level from the standard atmosphere. F_0 is the static thrust at sea level standard conditions, and F/δ is the net thrust. Unlike BADA TSCF model, which uses linear or quadratic relationship on the velocity, the corrected TSFC model establishes a linear relationship on velocity and exponential relationship on the thrust such that the TSFC algorithm is on the same order of precision as the thrust model estimated by the Total Energy Model. Moreover, the TSFC is corrected by the square root of the temperature ratio.

The fuel flow rate calculated by above equations applies to all phases of flight. But in descending, an arriving aircraft switches its configurations, i.e. cruise, approach and landing, when reaching certain altitude thresholds. There is a minimum fuel flow rate corresponding to the idle thrust settings:

$$f_{\min} = C_{f3}(1 - \frac{H_p}{C_{f4}})$$

where H_p is pressure altitude, and C_{f3}, C_{f4} are aircraft type specific coefficients. This equation indicates that the minimum fuel flow rate only linearly relates to altitude regardless of the aircraft configurations. Figure 4 compares the fuel flow rate of a step-downs trajectory to its CDA version against their vertical speed profiles. For CDA, the fuel flow rate drop to the minimum value when pass the TOD. In contrast, the fuel flow rate of step-down trajectory stays at high level whenever the aircraft execute level-flights. There is a noticeable fuel increase in low altitude level flight. It can be seen that the modeled speed profile is really close to the observed speed profile. Therefore, the fuel burn difference is largely caused by the vertical profile change.

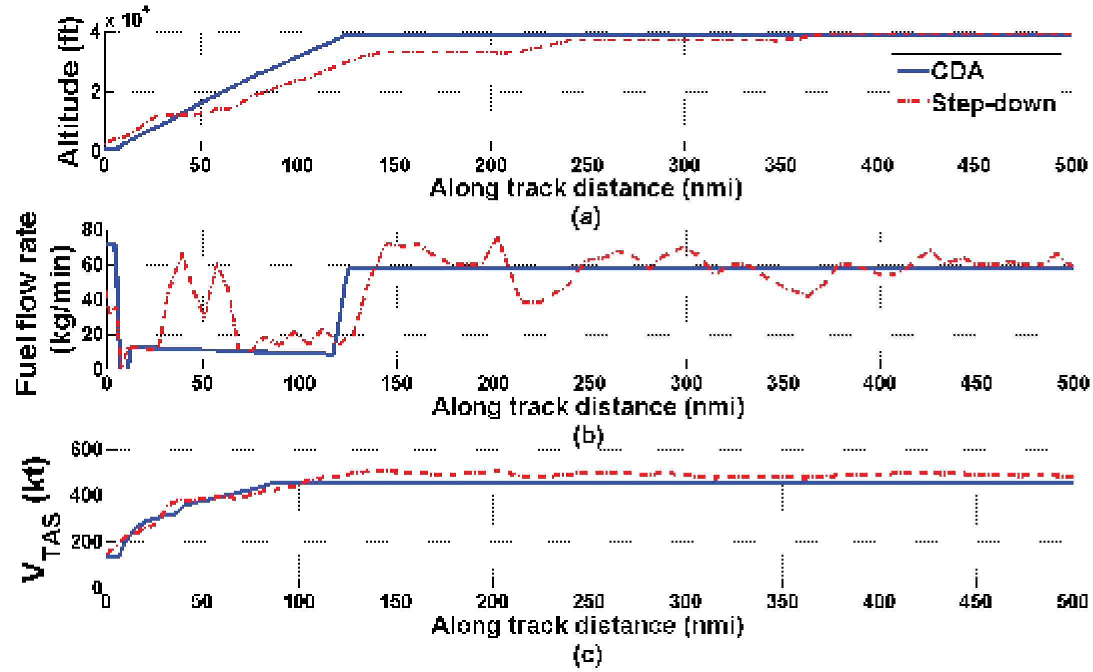


Figure 4 A sample of a B737 step-down and modeled CDA (a) vertical profiles, (b) fuel flow rate profiles (V_{TAS} = True Airspeed in knots), and (c) ground speed profiles.

Deconfliction Model

A problem associated with CDA is the predictability of speed profiles. Conventional step-down divides the descent into several segments such that the ATCs get a chance to re-predict the speed of arriving aircraft and issue advisory for adjustment during each level flight. Such chance is diminished in CDA scenario. The variability in the vertical and speed profiles among aircraft increases uncertainties. Even for an individual aircraft, uncertainties in the speed profile grow as CDA proceeds. Therefore, controllers are tempted to use increased separation minima to account for the uncertainties.

The deconfliction model stems from the Constrained Position Shifting due to Dear's work (25). Given an incoming arriving aircraft set *F* in time horizon *T*, the 4D trajectory of flight *i* can be represented by waypoints:

$$p_i(t) = < \varphi_i(t), \lambda_i(t), h_i(t) > \quad t \in [0,1,2,\cdots T]$$

where $\varphi_i(t), \lambda_i(t), h_i(t)$ are latitude, longitude and altitude associated with time stamp *t*. For all flights in the set, pairwise check can be made to probe conflicts during the descent phase:

$$< p_i(t), p_j(t) > = \begin{cases} false \; \|h_i(t) - h_j(t)\| > H \\ true \; \|h_i(t) - h_j(t)\| \le H \;\&\&\; d_{ij}(t) < D \end{cases} \qquad \forall t \in [0,1,2,\cdots T], \;\; i,j \in F$$

where

$$d_{ij}(t) = 2r \times \arcsin\sqrt{\sin^2\left(\frac{\Delta\varphi(t)}{2}\right) + \cos\varphi_i(t)\cos\varphi_j(t)\sin^2\left(\frac{\Delta\lambda(t)}{2}\right)} \;,$$

r is the radius of the earth, and $d_{ij}(t)$ is the great-circle distance between two waypoints computed by the HAVERSINE formula. *H* and *D* are the minimum vertical and horizontal separations. Normally, *D = 5 nm* in the en route airspace, and H=1000 ft below FL290 and H = 2000 ft above

FL290. In landing and takeoff operations, the preceding and following flights are subject to the wake vortex separations, as shown in **Figure 5**. The FAA wake vortex category is listed in **TABLE 2**. When two flights are in conflicts, one of the flights must be delayed to stagger the conflicted pair. In busy terminal environment, an aircraft may involve in multiple conflicts. To determine the conflict-free arrival sequence with minimized total delays, define a decision variable vector for flight *i*:

$$w^i = [w_0^i, w_1^i, \cdots w_L^i]$$

where w_k^i is a binary variable corresponding to a delay of $k\Delta t$, where Δt is the time interval. If flight i is assigned delay $k\Delta t$, then $w_k^i = 1$; and $w_k^i = 0$ otherwise. The maximum delay allowed is L. The deconfliction problem is posted as follows:

$$\min \sum_{i=1}^{F} \sum_{k=0}^{L} c_k^i w_k^i k\Delta t$$

$$s.t.$$

$$\sum_{k=0}^{L} w_k^i = 1, \qquad w_k^i \in \{0,1\}$$

$$w_{k_i}^i + w_{k_j}^j \le 1, \qquad \forall \ < p_i(t + k_i\Delta t), p_i(t + k_j\Delta t) > \ = \text{true}$$

c_k^i is a penalty associated with delay $k\Delta t$. The cost function is the total weighed delay. The cost linearly increases with increased delay. The first constraint dictates that each aircraft has only one active delay. The second constraint is the separation constraint, which states that if two aircraft are assigned delays $k_i\Delta t$ and $k_j\Delta t$ respectively, and their delayed trajectories are in conflict, the second constraint ensures that such assignment is infeasible. Output of the formulation is an optimized delay assignment that results in conflict-free CDA inbound traffic.

The deconfliction model schedules traffic 1 hour into the future. Incoming arriving flight within the current time window are scheduled using the optimization scheme described above, and flights that are already scheduled in the preceding time windows are frozen and serve as constraints for flights in the current time window. The time window starts from the midnight of the day and rolls through the day.

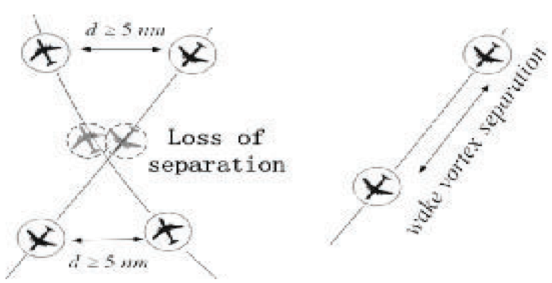


Figure 5 En route separation and wake vortex separation for preceding and following flights

TABLE 2 Wake vortex separation minima (nm) by aircraft weight class

Preceding	Trailing			
	Heavy	B757	Large	Small
Heavy	4	5	5	6
B757	4	4	4	5
Large	2.5	2.5	2.5	4
Small	2.5	2.5	2.5	2.5

Speed Change And Air holding

Delays resulting from the optimization scheme must be converted into an executable air traffic management advisory to take effect. Once a flight initiates a CDA descent, it is desirable to minimize the disruption to the descending flight. One feasible strategy is to apply the strategic deconfliction resolutions to en route airspace. To avoid complexity, this study uses speed change and air holding to absorb delays. Since this study mainly focuses on the descent phase, it is also assumed that the speed change and air holding will not cause secondary conflicts in the en route airspace.

Figure 6 shows a case where a B737 slows down before it hits the TOD in order to absorb a 2-minute delay. Figure 6 (b) shows the fuel flow rate (in kilograms per nautical mile) for the three scenarios. Compared to the CDA without delay, the CDA with delay experiences an increase on fuel flow rate. This is because the flight consumes more fuel within unit distance due to lower speed. In the case the flight has to absorb a high delay, and there is not enough along track distance to absorb that delay. The simulation simply holds the flight in the air and releases it later. This is to mimic the real-world air holding strategy.

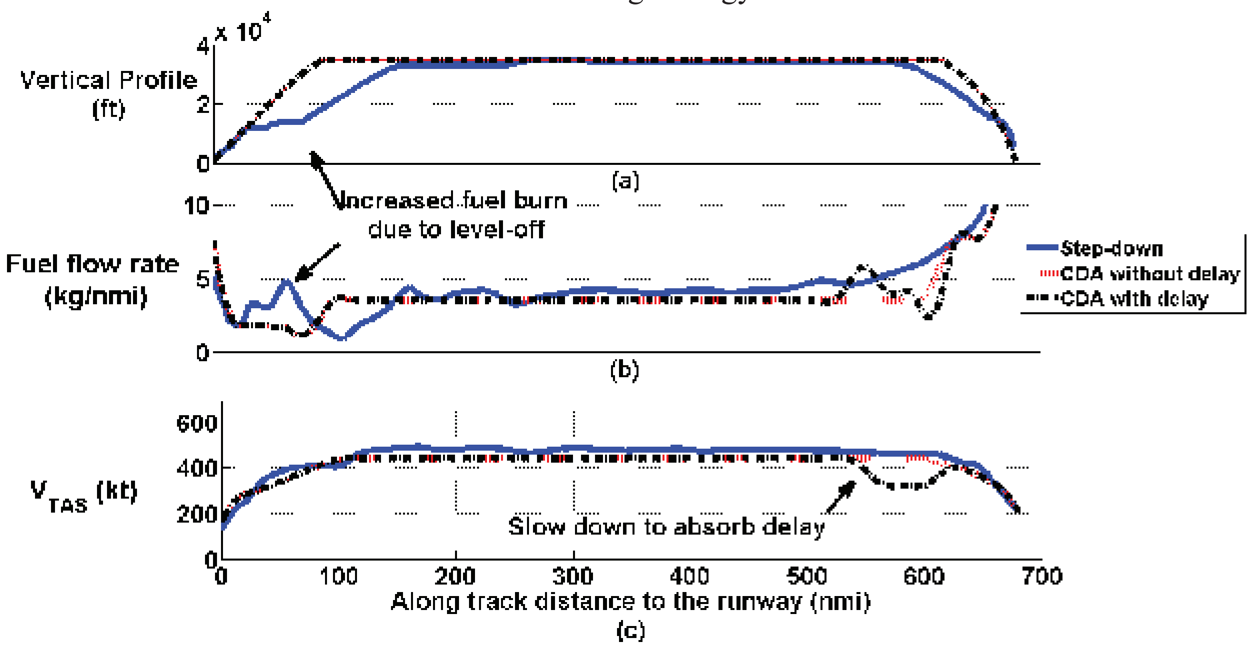


Figure 6 B737 decelerates to absorb a delay of 2 minutes when switching to cruise mode. (a) Vertical profiles. (b) Fuel flow rate profiles. (c) Ground speed profiles.

RESULTS

This section presents the simulation results. Two weeks inbound traffic flying into ATL between October 1st and 14th in 2011 are used for data analysis in order to increase the statistical significance. Table 3 summarizes the dataset size and the number and percentage of flights culled from this sample for analysis of the air traffic routing profiles for capacity/delay analysis and for the fuel consumption analysis. Thirty-five percent of the arrivals in the dataset, 6225 arrivals, are excluded from fuel analysis due to the lack of particular aircraft type specific coefficients in the corrected TSFC database. Anomalies in the radar track data resulted in the exclusion of 1041 arrivals. Approximately 94.1% of the arrivals are simulated, and 58.8% of which are used for fuel analysis.

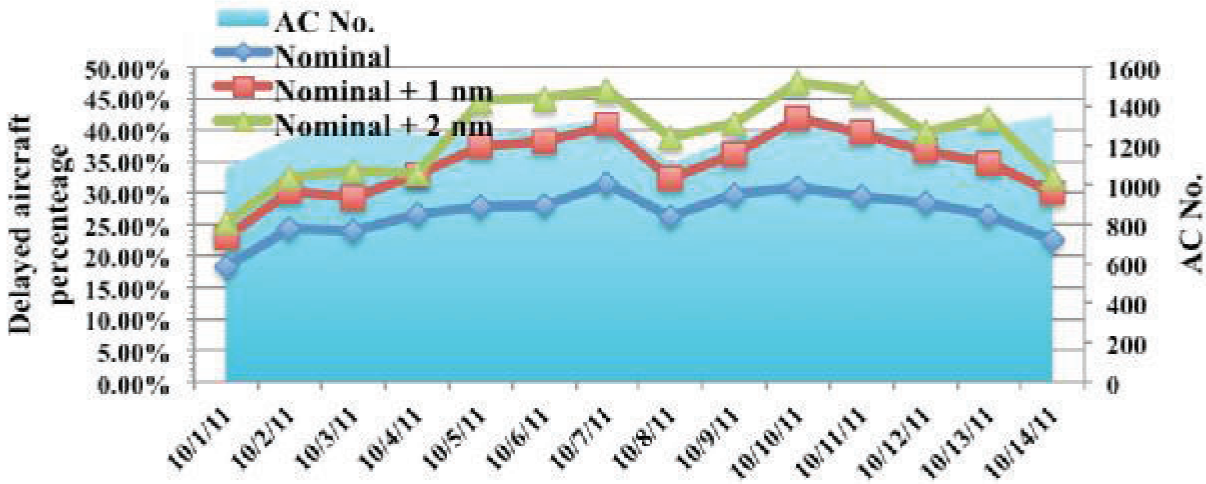
Table 3 Description of Culled Arrival Flights Dataset for ATL Oct 1 -14, 2011

	No. Arrivals	Percentage of Arrivals Simulated	Percentage of Arrivals Fuel Flow Analyzed
Total Arrivals	17,673	100%	100%
Arrivals excluded due to unavailable corrected TSFC data	6,225	N/A	35%
Arrivals not simulated due to radar track anomalies	1,041	6%	6%
Arrivals used in analysis	10,407	94.1%	58.8%

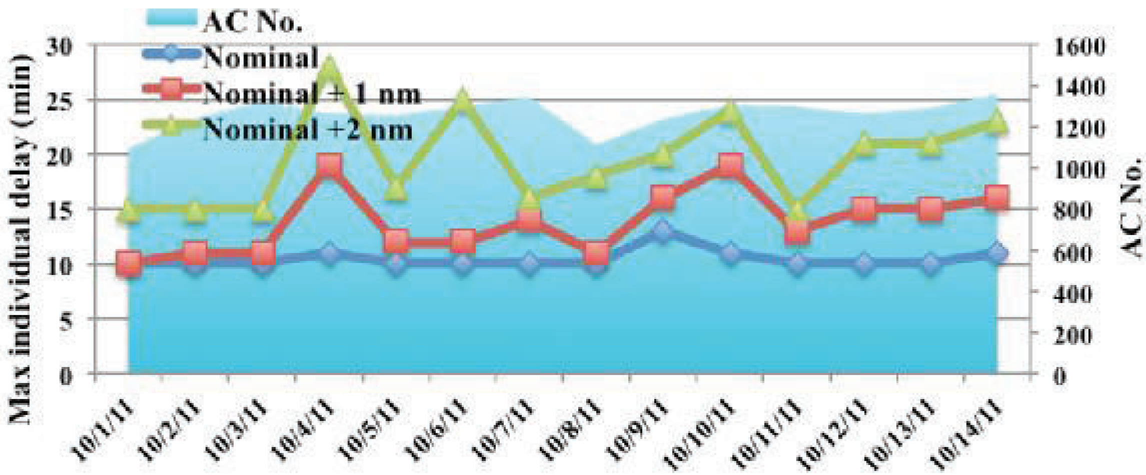
Influence of CDA Separation Uncertainties

The separation minima listed in **Figure 5** and **TABLE 2** is a general guidance for conventional step-down flights, denoted as nominal. In CDAs, ATCs use larger separations to accommodate uncertainties. To evaluate this impact, a buffer is added to the nominal separations, denoted as nominal+1 nm and nominal+2 nm. The increased separations are applied to the deconfliction. Metrics to measure the impact involve delayed aircraft percentage, the maximum individual delay and the total delays throughout daylong operations, which are shown in Figure 7. If flights change to fly CDAs, approximately 25%~30% (see Figure 7 (a)) of the total arrivals need to adjust their arrival times for conflict avoidance under nominal separations. But the percentage increases to 45% if a 2-nm buffer is added. The maximum individual delay posts an upper bound for the delay that the arrival flights have to experience (see Figure 7 (b)). Under nominal separations, flights experience delays less than 10 minutes, which can be readily absorbed by speed change or path stretching. When subject to higher separations, flights have to suffer from higher delays. This can be confirmed by reading Figure 7 (c). The total delay doubles when the 1-nm buffer is added, and may even triple when a 2-nm buffer is added. This observation implies that when CDA is flown, there is a great chance that airport throughput efficiency is negatively affected. If the deconfliction delays are to be absorbed in cruise phase, CDAs pass the negative impact backward to the en route airspace.

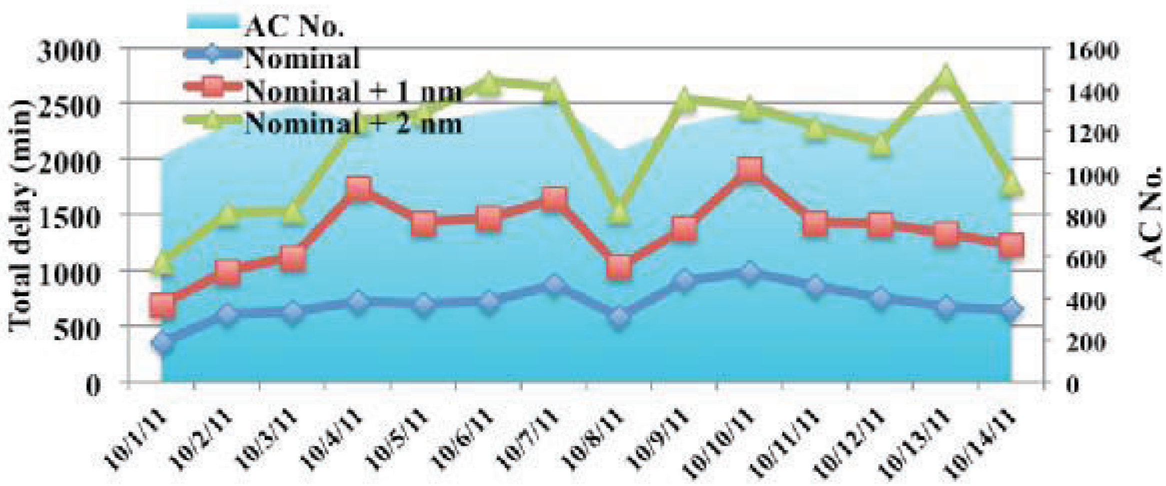
As the separation minima results in a significant difference in the total delay that will be translated into fuel burn, the magnitude of estimated fuel savings is contingent upon the separation minima used. In the next subsection, delays resulting from the nominal+2 separations are used for fuel analysis.



(a) Delayed aircraft percentage



(b) Maximum individual delay



(c) Total delay

Figure 7 Influence of increased separations.

Fuel Savings Estimation

For a given trajectory, applying the corrected TSFC model to each waypoint produces a footprint of fuel flow rate along the trajectory. Then, the fuel burn can be estimated by integration. To calculate the fuel savings due to CDA vertical profile, fuel burn of both the baseline trajectory and the corresponding CDA trajectory must be computed first. For the step-down trajectory, the fuel burn is counted starting from the TOD then all the way down to the runway threshold. Denote the baseline fuel burn for flight *i* as:

$$fuel_i^{step-down} = \int_{t_{ToD}^{step-down}}^{t_{landing}^{step-down}} f_{nom}(p_i(\tau), V_{TAS}(\tau))d\tau$$

The integrand, i.e. fuel flow rate, is a function of 3D position and the true airspeed, both of which can be obtained form PDARS data. For the CDA trajectory, the fuel burn is computed as follows:

$$fuel_i^{CDA} = \int_{t_{ToD}^{CDA}}^{t_{landing}^{CDA}} f_{\min}(h_i(\tau))d\tau + \int_{t \cong t_{ToD}^{step-down}}^{t_{ToD}^{CDA}} f_{nom}(p_i(\tau), V_{TAS}(\tau))d\tau$$

The first term corresponds to the idle thrust descent starting at the CDA TOD. The second term counts fuel burn from the step-down TOD to the CDA TOD. Then it is easy to compute the fuel savings:

$$f_i^{saving} = fuel_i^{step-down} - fuel_i^{CDA}$$

To account for the extra fuel burn due to delays, subtract the fuel burn for CDA without delay from that for CDA with delay.

$$fuel_i^{delay} = \int_{t_{takeoff}}^{t_{ToD}^{CDA}} f_{nom}(p_i(\tau), V_{TAS}^{CDA\_delay}(\tau))d\tau - \int_{t_{takeoff}}^{t_{ToD}^{CDA}} f_{nom}(p_i(\tau), V_{TAS}^{CDA\_nodelay}(\tau))d\tau$$

The overall fuel savings for flight *i* is the difference between f_i^{saving} and $fuel_i^{delay}$.

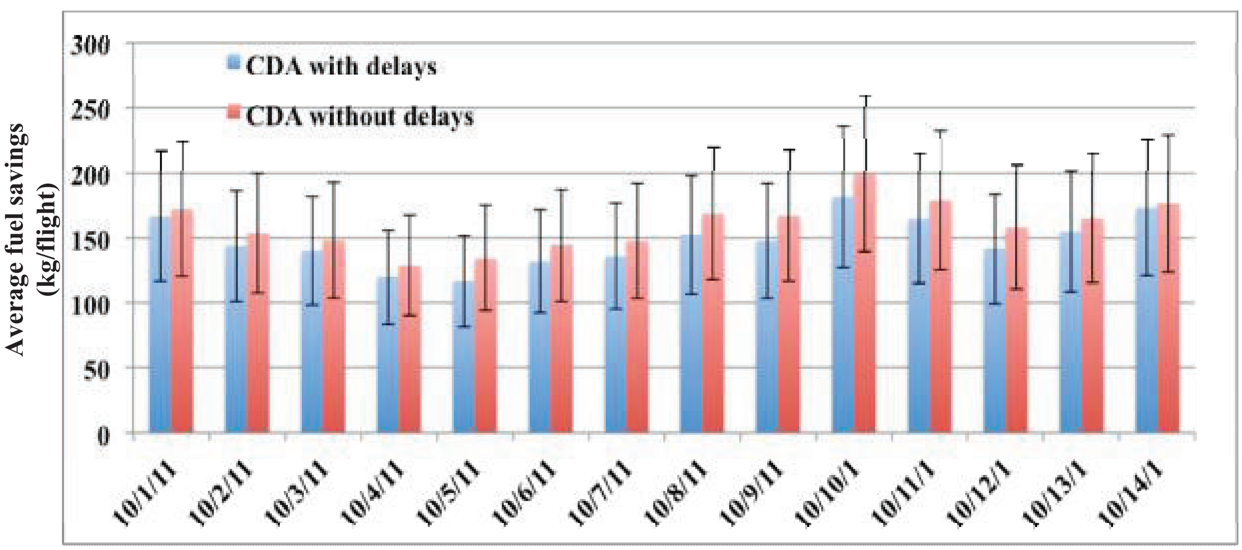


Figure 8 Average fuel savings with and without delays (with ±30% errors).

Figure 8 shows the average fuel savings on each day. Given that the fuel burn estimated by the corrected TSFC is bounded by 15%. The bias of the fuel difference should be bounded by 30%. The mean value of the fuel savings of CDA with delays is 147.99 kg/flight with a standard deviation of 18.41 kg/flight. The mean value of the fuel savings of CDA without delays is 160.22 kg/flight with a standard deviation of 18.27 kg/flight. The variations of data for both cases are relatively small compared to the mean value, so the observations are quite consistent throughout the two weeks period. Delays results in a 12.23 kg/flight reduction in the fuel savings on average, equivalent to 7.63% of the savings attributed to the CDA vertical profiles. This estimation is in accordance with the observations by a field evaluation by Coppenbarger et al. (26), where a 13.5 kg reduction of fuel savings per flight due to traffic was found, even though the absolute saving values may vary from 180 kg/flight to 2700 kg/flight.

Figure 9 provides another view for the impact of delays. It shows the distributions of fuel savings across all samples. The green and yellow lines outline the envelops of the distributions. The majority of CDA arrivals save fuel that is less than 400 kg. There is an apparent trend that the distribution shifts toward negative fuels saving values, indicating that delays cause a decrease in the fuel savings.

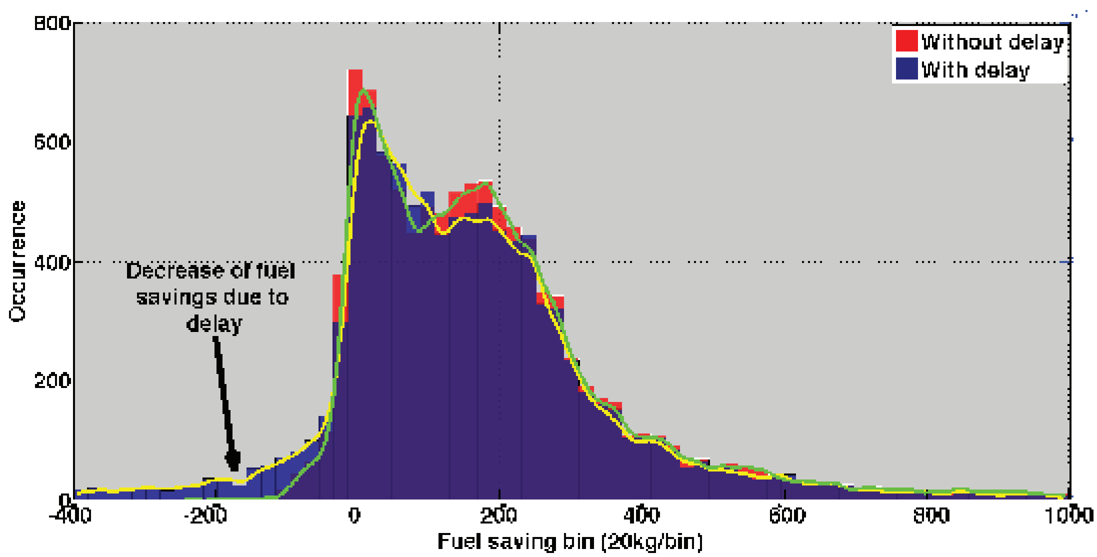


Figure 9 Fuel savings distribution across a sample size of 10407 arrivals.

Figure 10 presents the fuels savings by aircraft type. There were 63 different aircraft types found in the dataset, but only those whose sample sizes are bigger than 200 are shown here. There is a noticeable variation among different aircraft types, which is easy to understand since the aircraft weight class has a noticeable influence on the fuel burn. Even for a particular aircraft type, the variation is also significant, e.g. A320, B738, B752 etc. Two reasons account for the wide spread of data. First, as the CDA retains an almost constant descent gradient, the vertical profiles a CDA flight can fly is almost fixed once its speed profile (aircraft type specific) is selected, so is the fuel burn. But the baseline trajectories have a variety of vertical profiles with varying level-flight parameters, e.g. number of level-flights, distance of each level-flight and altitude where level-flight is executed. All these parameters are contingent upon traffic conditions and descent procedures chosen, and cause the baseline fuel burn to vary. As a result, the fuel saving numbers vary accordingly. Second, the delays resulting from the deconfliction

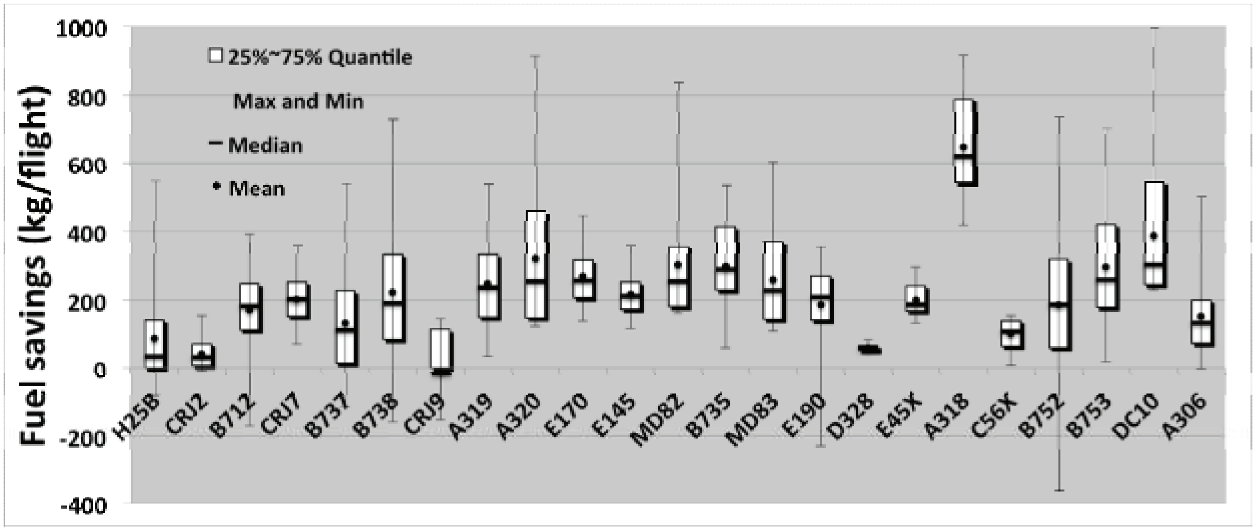


Figure 10 Fuel savings (with delays) by aircraft types.

procedure influence the fuel burn as well. The delay a CDA flight receives depends on traffic conditions in the proximity of the aircraft, which make it a random variable.

A close examination of the first reason is presented in Figure 11, Figure 12 and Figure 13. Two groups of A320s from Memphis and Phoenix are culled from total 283 A320 arrivals. All these A320s follow ERLIN NINE into ATL. Compared to the group from Phoenix, the Memphis group flies a relatively short distance. However, aircraft from both groups start continuous descent between 70 to 80 nmi away from the airport, resulting in similar CDA patterns. For the Memphis group, it is observed that the aircraft execute one level flight at around 10,000 feet above the ground level. Above that level, the aircraft descend smoothly, which leads to lower fuel flow rate than CDAs. In contrast, the aircraft in Phoenix group execute multiple level flights after TODs. Particularly, intermediate cruises between 100 and 200 nmi are noticeable. Fuel burn during this segment are mostly comparative to that of CDAs. On the other hand, the Phoenix group begins descents earlier than the Memphis group does, leaving more space for level flights. In other words, flight segments between the CDA TODs and the Step-down TODs leaves little space for offsetting the fuel burn difference in the subsequent low altitude flight. As a result, higher saving values are observed in the Phoenix group. Figure 13 shows the relationship between the number of level flights observed in the baseline trajectories and the corresponding fuel saving numbers for the total 283 A320s. The trends of both the mean values and the median values indicate that the savings are almost linearly correlated to the number of level flight executed.

Among the presented aircraft types, A318 shows a high potential of savings. A close examination of the sample population reveals that the majority of the A318 arrivals take a long range flight. Intermediate cruise altitude and multiple level flights are observed as in the Figure 12. Therefore, the descent procedure is one of the important factors that influence the saving numbers drawn from the comparisons.

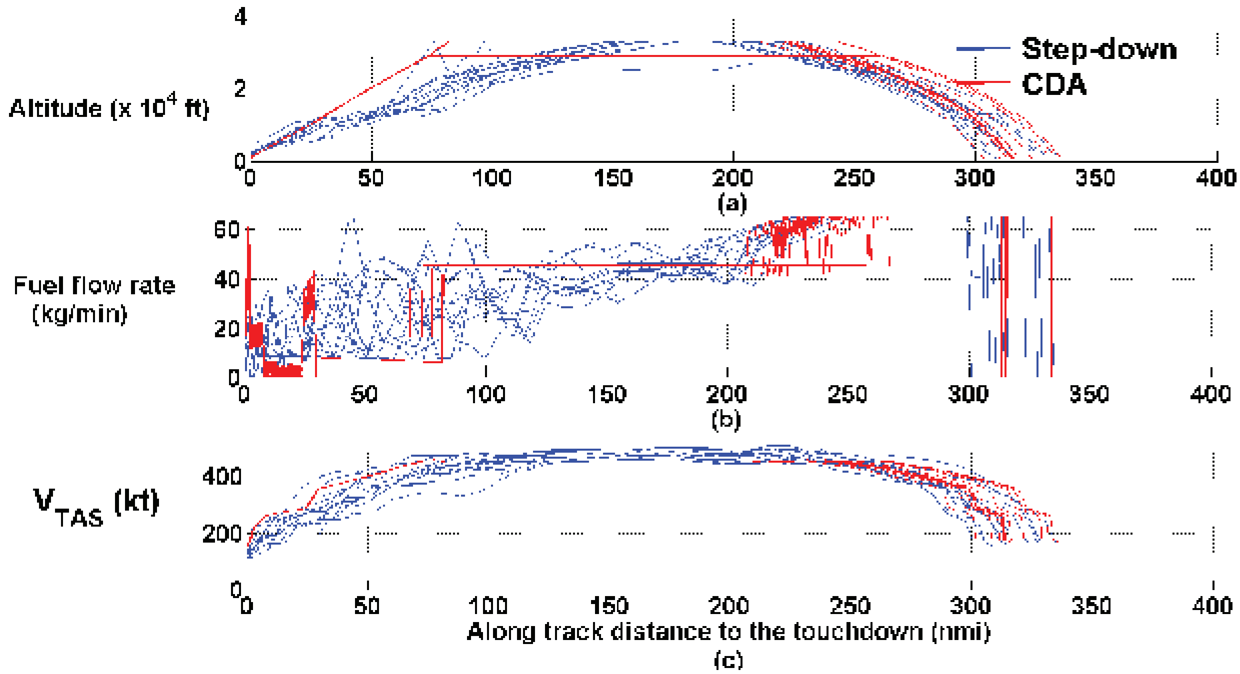


Figure 11 Ten A320 arrivals depart from MEM, and follow ERLIN NINE into ATL. The fuel savings of this group range from 150 to 300 kg. (a) Altitude profiles. (b) Fuel flow rate profiles. (c) True airspeed profiles.

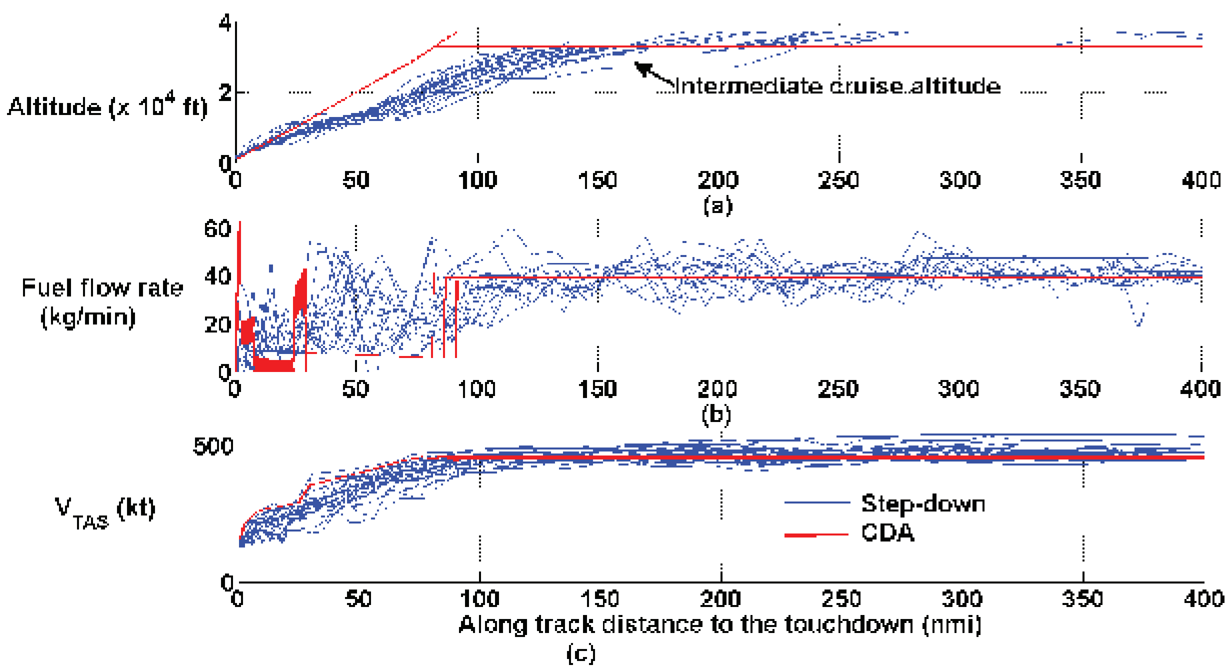


Figure 12 Twelve A320 arrivals depart from PHX, and follow ERLIN NINE into ATL. The fuel savings of this group range from 350 to 500 kg. (a) Altitude profiles. (b) Fuel flow rate profiles. (c) True airspeed profiles.

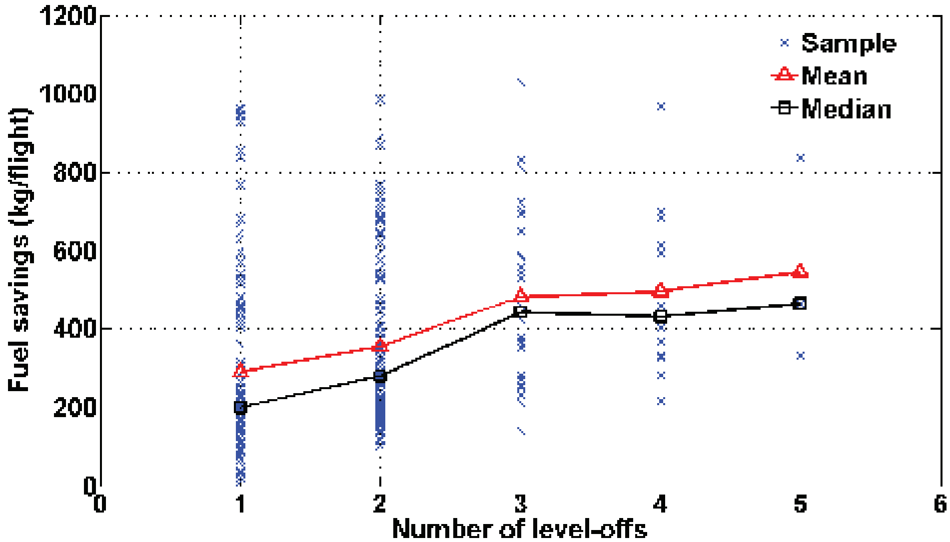


Figure 13 Relationship between the number of level flight and fuel savings for A320. Sample size = 284.

CONCLUSION

A simulation-based assessment of Continuous Descent Approach is reported in this paper. The CDA trajectories are based on FACET simulation with radar track data as input. The synthesized trajectories share the same ground tracks with the recorded trajectories such that the fuel savings is a consequence of change of vertical and speed profile only. A corrected TSFC model is employed to calculate the fuel burn. This model provides higher precision than the original BADA TSFC model in fuel estimation. The principal contribution of this study is that the CDAs are evaluated under increased separation constraints such that the estimation of fuel benefits takes into account ATC control.

Simulation results suggest that the average fuel savings for each arrival flight is 147.88 kg/flight, falling within the range of the IATA reported number 50~200 kg/flight. Individual negative fuel savings are also observed. But, airport wide, CDA is still fuel efficient. The fuel savings is less than that observed during the descent phase only. A 12.23 kg/flight reduction in the fuel savings is found due to the delays resulting from a deconfliction algorithm. It is also found that the increased separations have a significant impact on the delays calculated. Such impact potentially decreases airport throughput, thus can be deemed as a tradeoff of use of CDA as a terminal operation procedure.

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