FORMULATIONS AND COGNITIVE ENGINEERING MODELS

FOR

Optimizing Aircraft Sequencing and Spacing in the Terminal Area Airspace to Increase Airport Capacity, Reduce Fuel Burn and Emissions, and Reduce Noise on Developed Terminal Paths

A

Next Generation Air Transportation Project

Prepared by

Georgia Tech
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AND

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AMENDMENT HISTORY

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BACKGROUND

This document provides the description of different formulations and cognitive engineering models as specified in the Aircraft Sequencing and Spacing Optimization Sponsored Work Agreement and in accordance with DTFAWA-05-A-00005 – Task Order E1-07, Schedule of Work Subtask 2. This document surveys various formulations and cognitive engineering models that have been used to simulate the air traffic control system in the terminal area; and provide an analysis of the selected formulations and cognitive engineering models that will be applied to this project for the Memphis Terminal Area.

The different formulations and cognitive engineering models will be evaluated based on their ability to simulate the air traffic control system in the Memphis Terminal Area using emerging technologies such as the Ground Based Augmentation System (GBAS); Terminal Area Path (TAP) Procedures; real time two-way information exchange; and dynamic sequencing applications in an effort to illustrate the following benefits in the terminal area:

1. Decreased Fuel Burn and Emissions
2. Reduction in Noise
3. Increased Approach Availability
4. Decreased Minima where possible
5. Optimized Aircraft Sequencing in Real Time
6. Stable Arrival/Approach Procedures to Terminal Area Operations
7. Constant Rate of Descent Throughout Arrival and Approach
8. Minimized Flight Time in Terminal Area
9. Minimized Impact to ATC

The contract effective date is August 17, 2007 and delivery milestones will be as detailed in the Sponsored Work Agreement.

Figure 1 below shows the scope and operational concept for optimizing the aircraft sequencing and spacing in the terminal airspace during the simulation and flight test/demonstration in the planned terminal area test bed at Memphis airport.

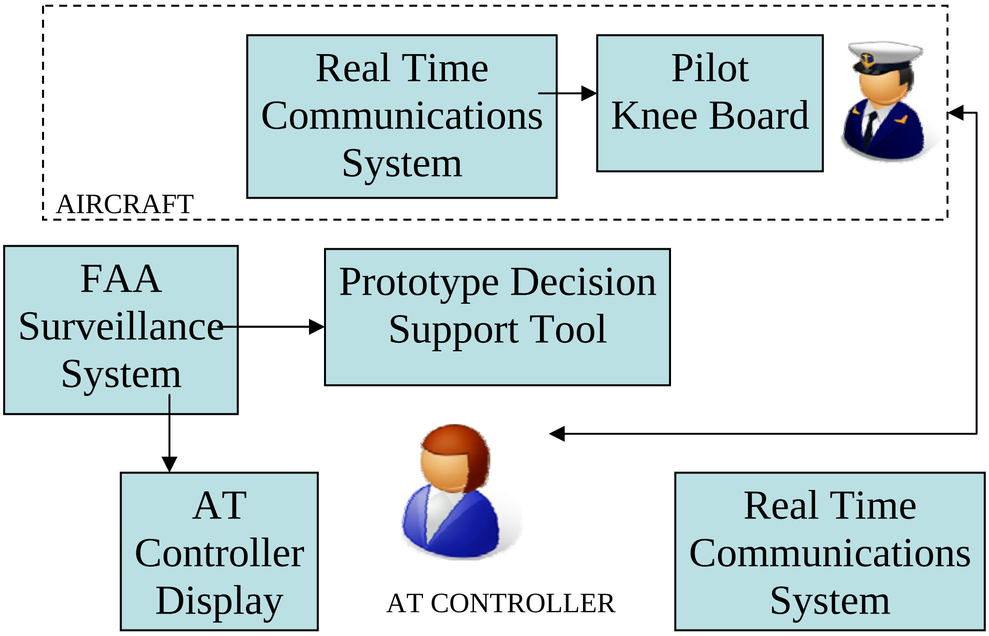


FIGURE 1 – SCOPE AND OPERATIONAL CONCEPT

1a. Description of Terminal Area Airspace (TAA)

The terminal area airspace (TAA) at many airports today are reaching and have reached their maximum capacity and many plans to increase the size of the airports and the number of runways have been blocked because of environmental or other issues that affect the local community around those airports. In addition, many terminal areas are confined in their airspace due to the requirements to reserve certain airspace exclusively for military aircraft and to place airspace around critical facilities, such as the White House, off limits for all aircraft. FAA and Department of Transportation methods to control demand and capacity, such as access restrictions; peak period landing fees; slot allocations; and slot auctions can sometimes help or hinder expansion plans. One possible solution at many large cities has been to add domestic and smaller commuter airports to help relieve congestion at the large international airports. However, the requirements for separation of aircraft during their long final approach paths to the different runways and airports have itself created congestion and vectoring of aircraft to long circuitous routes in the TAA. The longer more inefficient flight paths lead to increased fuel burn and emissions and more terminal area noise. However, the net result is that only 3 new airports will be built to alleviate these busy hub airports in the next 10 years, while airport operations is expected to grow by 150% over the next 20 years as predicted by the FAA.

The quantity of air traffic continues to grow steadily with increasing pollution of the air and the noise spectrums from TAA air traffic jams. Consequently, many aircraft are relegated to long airborne queues or holding patterns when arriving at an airport and wait in long queues on the airport surface for departures. All the while, they are burning fuel and making noise thereby adding to the environmental problems at every airport. Finally, the airlines are still in the recovery mode after 9/11 and the SARS epidemic, and their full recovery will put tremendous pressure on the capacity requirements at all the major airports in the US.

1b. Issues and Problems in the TAA

With increasing demand for landing and airport resources, the current issues and problems within a TAA must be resolved or mitigated so that additional demand can be accommodated by optimizing aircraft flight tracks, sequencing, and timing in the TAA. This will minimize fuel burn, emissions, and noise from each flight and reduce ATC controller intervention and vectoring which will reduce controller workload. The current issues and problems in the TAA are:

- Airports and Airlines Lack Precise Positioning Data
- Fuel Burn and Emissions Cost Airports Community Goodwill
- Continuous Aircraft Data Communications is Vital
- Precise Flight Tracks are Needed for Constant Descent Approaches
- Timing and Sequencing Increase Efficiency

1b1. Airports and Airlines Lack Precise Positioning Data

An aircraft’s exact current location is not available to either airport or airline operations once it is outside the terminal area. Using data like the take-off time, heading, and aircraft performance specifications for each aircraft in the fleet, airlines estimate destination arrival time in their schedules, and airports look to make contact with arriving aircraft as they reach the outer radius of the terminal airspace. Any deviation from the expected can lengthen the flight track of an aircraft, and like dominos, one aircraft’s deviation can affect any number of flights behind it. Due to the lack of position certainty with most aircraft in terminal area airspace, air traffic controllers depend heavily upon radar control and they make approach corridors extra wide and keep aircraft separated by large margins to preclude mid-air collisions. This need for separation also lengthens flight tracks, as each aircraft in turn needs to maintain an adequate distance from the one before it.

1b2. Fuel Burn and Emissions Cost Airports Community Goodwill

Fuel burn and emissions at airports are significant concerns to both airport users and the community at large. The increasing cost of fuel has a clear detrimental impact on airline profitability. Airline profitability, in turn, impacts airport profitability in reduced gate and services fees. Emissions, both fuel pollutants and noise, cause concerns regarding local air quality and quality of life around airports, especially at those airports that have not attained environmental compliance. Currently, most aircraft making precision landings use radar-guided approaches/transitions to the final approach segment. As noted above, these procedures usually require multiple changes in vector to line up incoming aircraft with the runway on which they land. Each change in vector is likely to require throttle adjustments to compensate for changes in approach speed and other aircraft variables as the pilot achieves the required altitude or azimuth—and each throttle adjustment generates more noise and fuel pollutants. The goal is a Constant Descent Approach (CDA) from the edge of the TAA all the way to the runway without any changes. This can be accomplished with a very efficient timing and sequencing algorithm so that all approaching aircraft can be merged and sequenced at the entry fixes located near the TRACON boundary, and assigned a CDA path that does not have to be changed in any way during the entire approach and landing.

1b3. Continuous Aircraft Data Communications is Vital

This investigation requires a data communications capability that can continuously transmit and receive the appropriate data points from each source—aircraft, airline, and airport—to enable real time calculation of the optimum location, airspeed, and descent profile for each aircraft as it approaches the terminal airspace. To ensure timely and sufficient data on each en-route flight, each aircraft must have a defined arrival time and maintain constant communications. The capability must provide two-way tracking and communications. It can provide collaborative decision making between all the parties in the system, and has the capability for users to receive all the commands similar to today’s voice system. The application must be usable as a universal location and message communication system with several unique characteristics: global, near real time, two-way over-the-horizon (OTH) secure data transmission; user-to-user communication; interoperability among users and organizations (if required); geo-location; high capacity; 24/7 availability, and security.

1b4. Precise Flight Tracks are Needed for Constant Descent Approaches

A LAAS ground facility (LGF) constantly transmits navigational messages up to any equipped aircraft within the terminal area airspace. An aircraft equipped to receive this data can use a Required Navigation Performance (RNP) procedure that has been calculated to provide the most efficient flight path and rate of descent to land without constant adjustments. This greatly reduces the necessary communication between the terminal area radar controller and the aircrew. An RNP-capable aircraft can receive clearance for the RNP approach at the outer fringes of the terminal area and no further navigational guidance transmissions are required until the aircraft is cleared to land. The aircrew is free to concentrate on getting the aircraft configured to land, thus reducing the cockpit workload and increasing their “situational awareness.” The LAAS LGF allows the FAA a unique capability to provide a service to older analogue aircraft which will facilitate the transition period to satellite service. That analogue service is provided through an up-linked terminal area path (TAP) which will provide an equivalent RNP level of service.

1b5. Timing and Sequencing Increase Efficiency

Researchers at the Georgia Institute of Technology have developed a very efficient, two-stage heuristic algorithm for optimizing the sequence of arriving aircraft and the fairness in terms of the number of positions in the arrival queue that any one aircraft can be moved back to achieve better throughput or reassigned to another runway end without loss of time and landing sequence. They point out in their analysis that even greater increases in throughput could be achieved if the arriving traffic were re-sequenced and re-timed en route. In addition, Georgia Tech has developed a mixed-integer linear program with an embedded search for optimizing the flight speeds and flight levels of aircraft en route, thereby reducing delay and fuel burn. In the algorithm they developed, they determined the optimum altitude and speed of each aircraft by searching for the speed and altitude that kept the aircraft closest to the operating condition where its operating cost was minimized. They explicitly considered aircraft performance limits such as maximum speeds and service ceilings. Their analysis of the algorithm showed that up to 8.5 minutes of delay could be mitigated on average in the Northeast corridor of the U.S. when traffic levels increase to those for which NGATS is being designed. The resulting reduction in fuel burn and emissions (and their effects on both local and global air quality) would help to relieve the constraint that the environmental impact of aviation places on growth. As is to be expected, optimization of traffic flows in general, and the movement of individual aircraft in particular, requires precise knowledge of the location and the potential future trajectories of each aircraft, as well as aircraft with the ability to precisely follow a prescribed trajectory. There are at least four reasons why LAAS TAPs and the continuous aircraft data communications provide an avenue through which such optimization could be implemented. First, the GPS-based LAAS system provides very accurate estimates of current aircraft location. Second, the algorithms that have been developed to generate the LAAS TAP must by definition consider all the potential future trajectories of each aircraft, thus they can be readily provided to the optimization algorithm. Third, the LAAS TAP already provides mechanisms for precise trajectory following. Fourth, the continuous aircraft data communications equipment provides the dynamic data from aircraft in the terminal area that is required for conformance monitoring, as well as the communication mechanism to adjust trajectories if required. The investigation of optimizing spacing and therefore, proper sequencing of aircraft, is a natural combination research accomplished at the Georgia Institute of Technology and the LAAS TAP research.

1c. Scope of Contract for Optimizing Aircraft Sequencing and Spacing

This project will be conducted in two tasks over a two year period, and conducted as two phases. The scope of the first task or first phase has been addressed in the project plan (Reference vi) and will be conducted in the first year of the project. The project plan will be updated when the second task is awarded in 2008. The first year plan addresses project planning and development, including analysis, tool development, NAS integration approach, and operational procedure development required for the first phase. The second phase will consist of establishing the test bed and conducting the flight trial scenarios developed under the first phase.

The following are the subtasks that were awarded to ISI on August 17, 2007 for the first phase, which will end on August 17, 2008:

Subtask 1: Coordinate with airline, industry, academia, and airport personnel to reach agreement with the project objectives and understand air traffic controllers' national and local constraints. Develop and provide written Project Plan.

Subtask 2: Develop different formulations and cognitive engineering models to support the terminal area airspace issues and operations, and provide written report on formulations and cognitive models.

Subtask 3: Mathematical and cognitive engineering models of the operations at an airport, that can be used in future JPDO work related to airport operations. Provide written report on feasible concepts for optimizing the sequencing and timing of aircraft and in the terminal area airspace to increase airport throughput and reduce fuel burn and emissions.

Subtask 4: Integrate prototype decision support tool with the surveillance tool methodology and required flight operations. Provide draft design of TAP procedures and draft design of integration of two-way Real Time Communications Systems.

Subtask 5: Design TAP procedures for an airport and a design to integrate a prototype two-way Real Time Communications Systems.

This document is the deliverable for Subtask 2, where different formulations and cognitive engineering models will be developed and evaluated to determine the best aircraft sequencing and spacing model that will be used to simulate and flight test aircraft in the Memphis TAA in order to demonstrate increased airport capacity, reduced fuel burn and emissions, and reduced noise on approaches to the Memphis airport.

OBJECTIVES OF SUBTASK TO DEVELOP FORMULATIONS AND COGNITIVE ENGINEERING MODELS

The objective of this Task Order E1-07; is to be able to illustrate the nine benefits as defined in Section 1. Subtask 2 of this task order is to evaluate the different formulations and cognitive engineering models that can be used to generate the dynamic sequencing commands for arriving aircraft at an airport so that all of the nine benefits can be illustrated by the models. Except for benefit number 4; Decreased Minima where possible; a Continuous Decent Approach (CDA) procedure has the potential to provide all the other benefits listed in Section 1. A CDA is both an approach and an arrival procedure where an aircraft flies a higher altitude and lower trust, with a constant rate of descent, until interception of the ILS glide slope or NPA procedure; and with no need for any level flight segments. The CDA will then provide all the benefits needed for this task such as reducing noise with decreases in fuel burn and emissions. While the CDA may be easy to accomplish with one aircraft, the challenge is to provide CDA procedures to all arriving aircraft, at the boundaries of the terminal airspace area (TAA), properly merged and sequenced, so that no further commands or vectoring are needed from the ATC controllers until all the aircraft lands on the runway. This implies that the aircraft will all be properly spaced (according to the types of aircraft) on the final approach and landing segment. It is a further challenge to optimize capacity by making sure that when the aircraft are on the final approach segment they are all minimally spaced, again based on their aircraft types, in order to improve throughput. Finally, to reduce fuel usage and emissions, the CDA approach for every aircraft must be calculated to fit into the aerodynamics of each aircraft type in order to provide a constant descend with minimum trust, trust changes, or engines on idle. Therefore, if there are a set of formulations and cognitive engineering models that can generate those set of commands for each arriving aircraft so that on the final approach every aircraft will be minimally spaced (according to the types of aircraft) between each other and that the total fuel burn or emissions of all arriving aircraft are minimized, then the objectives of this task can be achieved and illustrated. The set of formulations and cognitive engineering models also has to be valid if the aircraft are arriving from two different streams of aircraft from opposing directions when they first arrive at the boundaries of the TAA.

FORMULATIONS TO SUPPORT TERMINAL AREA AIRSPACE

While developing an algorithm to meet the previously mentioned objectives, three formulations of an algorithm were developed. Each of the formulations, the one-speed change formulation, the two-speed change formulation, and the two-speed formulation with sequencing, will be described in this section, following a discussion of the terminal area airspace issues and operations.

3a. Terminal Area Airspace Operations and Issues

The runway capacity at an airport is limited by the physical configuration of the airport, the instrument and surface management system available at the airport, the type and equipage of aircraft operating at the airport, and the existing separation standards. While new technologies and infrastructural investments offer possible improvements, the process is lengthy and the potential for significantly increasing runway capacity at the nation’s major airports is limited, at least as we understand today. Thus, there are urgent needs to develop procedural means within the terminal area airspace to best utilize the available capacity on one hand, and to preserve economical and environmental efficiency on the other.

At major airports, arrivals are operating in a four-corner post configuration when traffic is high, to maximize throughput. In this configuration, arrivals to the airport merge at four entry fixes located near the TRACON boundary to buildup four arrival queues so that air traffic controllers can manage spacing between aircraft in each queue to best utilize the runway capacity at the airport. Depend on the actual airspace configuration, the number of the entry fixes (corner posts) at a specify airport may be more or less than four. In existing practice, the way to maximize runway throughput is to minimize runway idle time due to the randomness of inter-arrival time to the runway. Queuing delay is thus inevitable, and controllers have to use vectoring to adjust spacing between aircraft so that it can be as close to the separation minima as possible. The queuing delay and the vectoring, especially vectoring in the low altitude, will cause flight time and fuel burn to be higher than the minimum possible values[i,ii].

To improve efficiency in the terminal area airspace, the queuing delay and vectoring, need to be reduced. Terminal area procedures such as the RNAV based Continuous Descent Approaches and Arrivals (CDA) are developed with optimized lateral and vertical profiles so that aircraft can conduct a smooth and continuous descent without being extensively vectored at low altitude, and ideally with throttle set at idle most of the time to save flight time and fuel [see the two CDA references above]. Other RNAV arrival and approach procedures, such as those being developed for MEM, may not always possess the optimized vertical profile as an ideal CDA would have, could developed based on the same principle to reduce flight time and fuel burn over a conventional approach.

To help the controllers to manage spacing between aircraft performing these advanced RNAV arrival procedures, and thus to retain runway throughput at the same time, a theoretical framework of separation analysis has been developed[iii] and tested in real world operations at SDF[iv]. The Tool for Analysis of Separation And Throughput (TASAT) was developed to implement the aforementioned theoretical framework.

In TASAT, uncertainties associated with aircraft performing a RNAV based arrival procedure are analyzed and modeled to build a dynamic based stochastic aircraft trajectory simulator. Simulated trajectories, or trajectories from flight test or real world operations should they become available, are then fed into a probabilistic separation analysis algorithm to determine proper spacing or timing, referred to as target spacing, at a metering fix (may or may not be the corresponding corner entry fix) between aircraft type pairs. The target spacing or timing is determined such that spacing along the way to runway would be assured at a relatively high probability without extensive vectoring at low altitude; and the separation buffer is kept at a minimum.

Should the target spacing or timing be established at the metering fix, the RNAV based arrival procedure would be performed, at a high probability but not absolute, without being vectored at low altitude and without excessive separation buffer. As a result, the throughput could be retained and the efficiency improvement could be achieved. It is worth to point out that the target spacing is normally higher than the minimum ad hoc spacing that can be measured at the metering fix in existing operations. Thus, air traffic controllers in the upper stream sectors would need to spend more effort than what it is in existing operations to perform the merging and spacing task so that the target spacing or timing can be established for at least the most majority of the traffic, if not all. However, without proper tools, the extra effort of establishing the target spacing and timing at the metering fix would most likely require some rigorous vectoring when the aircraft are closer to the metering fix. This would offset some of the benefits that can be achieved within the terminal area.

To aiding the task of merging and spacing at the metering fix, speed advisory optimization algorithms have been developed to achieve best efficiency in cruise while establishing target spacing and timing that would allow the throughput and efficiency benefits in terminal area airspace. These algorithms are the subjects of the next subsections.

The TASAT as flight-tested at SDF, deals with the situation of managing separation for the traffic stream from a single metering fix to a single runway. At major airports, it is often necessary to merge the arrival streams (or portions of them) from different entry fixes to the final approach fix for a single runway. Work is under way to expand TASAT to handle the merging and spacing within the terminal area airspace. The enhanced TASAT will provide coordinated target spacing and timing for traffic to multiple metering fixes. The speed advisory optimization algorithms are also been enhanced to handle coordinated merging and spacing to multiple metering fixes at cruise.

3b. One-Change Formulation for Single and Multiple Streams

List of Variables for Formulations in 3b. – 3d.

$\dot{f}_i$ = Fuel burn for an aircraft at a given Mach number
j = Selected number of aircraft able to make a speed change
T_i = Total time of Mach speed change
t_i = Initial ETA
$t_{0,i}$ = Start time of first Mach change
t_D = Final ETA
Δt_i = Change in time from initial ETA
M_i = Initial Mach number
ΔM_i = Change in Mach number
M_{d_i} = Final Mach number
δ_i = Binary variable indicating whether this aircraft has a change in Mach
m = number of lines in the linear interpolation
$a_{i,m}$ = Slope of the m^th^ linear segment of a fuel curve
$b_{i,m}$ = y-intercept of the m^th^ linear segment of a fuel curve
$T_{i,R}$ = Time interval during which the aircraft returns to its original Mach.
$M_{bound,i}$ = Maximum or minimum bound on the Mach number change
t_r = Time at which aircraft returns to its original Mach
P_{f_i} = Percentage fuel burn at a given Mach number
$\dot{f}_{\min}$ = Minimum fuel burn rate

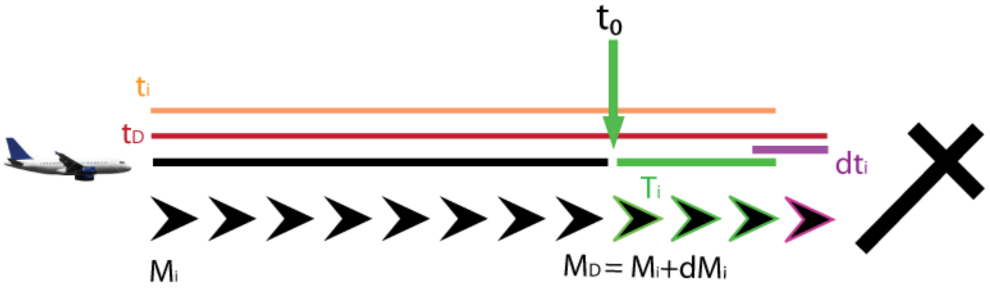


FIGURE 3.B.1- DIAGRAM OF VARIABLES FOR ONE-CHANGE FORMULATION

The one-change formulation was developed in order to test the feasibility of the solution procedure and provide a baseline for future optimization results.

The first part of the equation is the cost function, which simply states that the net fuel burn should be minimized across each aircraft.

$$\min Z = \sum_{n-1}^{N} \dot{f}_i T_i \tag{3b.1}$$

Following this equation are the necessary constraints on the objective function. It is first necessary to linearize the fuel burn curve for each aircraft involved in the CDA procedure. This process is equivalent to the following series of constraints:

$$\begin{aligned} \dot{f}_i &\ge a_{i,1} M_x + b_{i,1} \\ \dot{f}_i &\ge a_{i,2} M_x + b_{i,2} \\ &\vdots \\ \dot{f}_i &\ge a_{i,m} M_x + b_{i,m} \end{aligned} \tag{3b.2}$$

It will be important to have accurate fuel burn data for each aircraft type involved in the flight-testing. Next, a constraint is needed to limit speed changes to at most one speed change per aircraft:

$$\delta_i \ge \frac{|\Delta t_i|}{M_i} \tag{3b.3}$$

$$\delta_1, \delta_2, \ldots \delta_n \text{ binary} \tag{3b.4}$$

In addition, the maximum number of aircraft to perform the CDA can be selected with the following constraint:

$$\sum_{j=1}^{J} \delta_i \le j \tag{3b.5}$$

To ensure that the necessary spacing is maintained, the leading and following aircraft must have spacing greater than or equal to their TASAT-calculated separation:

$$(t_{i+1} - \Delta t_{i+1}) - (t_i - \Delta t_{i+1}) \ge S_{i,i+1} \tag{3b.6}$$

An important note for this formulation and the formulation described in Section 3c, is that these formulations assume the initial sequence of aircraft is fixed. These formulations assume a set order of aircraft based on the aircraft's initial estimated time of arrival (ETA).

In addition, while this formulation was intended for only one stream of arriving aircraft, it can be modified to include two non-conflicting streams. This task will be addressed in detail in the coming months. The modification would be to ensure that the arrival times for aircraft on multiple streams are staggered enough so that there will not be conflict in their arrivals. This will be accomplished through TASAT analysis. Once the desired timing is known and inserted into equation 3b.6, the cruise speed change will be calculated as described below.

It is then necessary to relate the change in ETA to the change in Mach number, assuming the change in velocity is much less than the cruise velocity, and that the cruise velocity is directly proportional to the Mach number:

$$\Delta V_i << V_i \qquad (3b.7)$$

and

$$V_i \approx a_{SOS_i} M_{x_i} \qquad (3b.8)$$

a relationship between time and Mach number can be derived:

$$\Delta t_i = T_i \frac{\Delta M_i}{M_i} \qquad (3b.9)$$

Lastly, it is necessary to limit the possible change in Mach number:

$$M_i + \Delta M_i \le M_{i,\max} \qquad (3b.10)$$

$$\left|\Delta M_i\right| \le \Delta M_{\max} \qquad (3b.11)$$

and calculate the net time during which the speed change is made, the final (decision) Mach number, and the final ETA. These tasks are performed by the following three constraints respectively:

$$T_i = t_i - t_0 \qquad (3b.12)$$

$$M_{d_i} = M_i + \Delta M_i \qquad (3b.13)$$

$$t_{f_i} = t_i - \Delta t_i \qquad (3b.13)$$

3c. Two-Change Formulation for Single and Multiple Streams

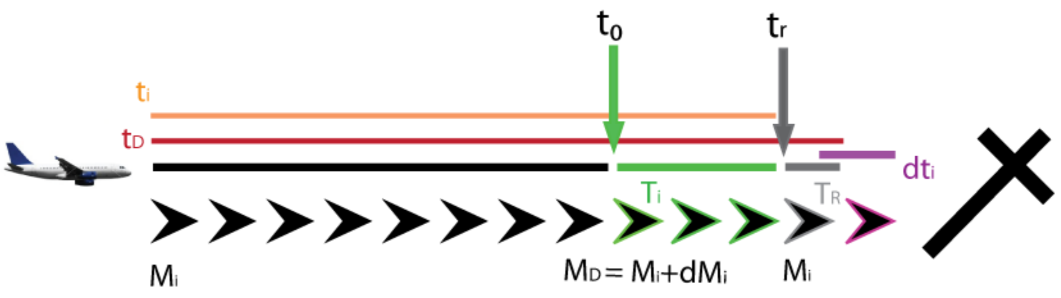


FIGURE 3.C.1 DIAGRAM OF VARIABLES FOR TWO-CHANGE FORMULATION

The difference in the one-change and two-change formulations is that the two-change formulation now allows aircraft to make a second speed change to return to that aircraft's initial cruise speed. The advantages of such a solution are less time deviating from the aircraft's initial cruise speed and greater accuracy in achieving the minimum spacing between aircraft. The two-change formulation has all of the same constraints mentioned in the previous section, save for a modified objective function and the relationship presented in equation 3b.9. Two streams of aircraft can also be handled in a similar manner as described in Section 3b. By modifying the target separation times for each aircraft stream, this formulation will still apply, altering the cruise speeds of the aircraft involved so that each arrives at the desired time. The objective function must now include the fuel burn during the second speed change:

$$\min Z = \sum_{n=1}^{N} \dot{f}_i T_i + \sum_{n=1}^{N} \dot{f}_i \Big|_{M_i} T_{i,R} \qquad (3c.1)$$

For two speed changes to be made, Equation 3b.9 needs an additional term, the time during which the aircraft resumes its initial cruise speed, $T_{i,R}$:

$$\Delta t_i = (T_i - T_{i,R}) \frac{\Delta M_i}{M_i} \qquad (3c.2)$$

Expanding this equation, unfortunately gives a nonlinear equation (only M_i and T_i are known):

$$M_i \Delta t_i - T_i \Delta M_i + T_{i,R} \Delta M_i = 0 \qquad (3c.3)$$

Nonlinear equations drastically increase the complexity of the problem, so it is then necessary to rewrite this equation to make it linear and provide additional constraints on the problem.

If we set the nonlinear term equal to another variable:

$$T_{i,R} \Delta M_i = w_i \qquad (3c.4)$$

we can rewrite the nonlinear equation as a linear one:

$$M_i \Delta t_i - T_i \Delta M_i + w_i = 0 \qquad (3c.5)$$

and provide necessary constraints on *w*, provided from Lebbah, Michel and Rucher.[v]

This paper constrains the values of *w_i* with the following equations (Note that $\underline{x}, \overline{x}$ denote the lower and upper bounds respectively on the variable *x*.):

$$\underline{M_{bound,i}} T_{i,R} - w_i \le 0 \qquad (3c.6)$$

$$\overline{M_{bound,i}} T_{i,R} - w_i \ge 0 \qquad (3c.7)$$

$$\underline{M_{bound,i}} T_{i,R} + T_i \Delta M_i - w_i \ge \underline{M_{bound,i}} T_i \qquad (3c.8)$$

$$\overline{M_{bound,i}} T_{i,R} + T_i \Delta M_i - w_i \le \overline{M_{bound,i}} T_i \qquad (3c.9)$$

$$T_{i,R} \geq 0 \tag{3c.10}$$

$$T_{i,R} \leq T_i \tag{3c.11}$$

$$\Delta M_i \geq \underline{M_{bound,i}} \tag{3c.12}$$

$$\Delta M_i \leq \overline{M_{bound,i}} \tag{3c.13}$$

$$w_i \geq \underline{M_{bound,i}} T_i \tag{3c.14}$$

$$w_i \leq \overline{M_{bound,i}} T_i \tag{3c.15}$$

There are also two additional constraints needed for the two-change formulation, ensuring that the time during which the aircraft returns to its original cruise mach is less than the total time of the first speed change:

$$T_{i,R} \leq T_i \tag{3c.16}$$

and the calculations of the total return time at cruise:

$$T_{i,R} = t_i - t_{i,R} \tag{3c.17}$$

All other constraints in the previous section hold.

3d. Two-Change Formulation with Sequencing for Multiple Streams

The optimum sequencing will be determined by enhancing the algorithm (to determine the optimal changes in the cruise speeds of a known sequence of aircraft to achieve the required spacing at the metering point) that has been described above to account for changes in the aircraft sequence. Specifically, the range of possible sequences will be enumerated, and then an assignment problem will be solved to determine the sequence of the arrivals that achieves the lowest objective function, where the objective function is a weighted sum of the economic and environmental efficiencies, and the constraints are the earliest and latest possible arrival time. A novel feature of this assignment problem will be the sub-problem in which the cost of achieving a given sequence will be determined using the aforementioned algorithm to determine optimal changes in cruise speeds. By incorporating this feature, the solutions that are developed using the algorithm will be globally optimal rather that just optimal for the descent.

An alternative method to allow for sequencing of the aircraft would also be to add to the constraints present in equation 3b.6. In the current algorithm, this equation only ensures that leading and following aircraft have the spacing required by TASAT. However, it would be possible to have a database of all leading and following aircraft combinations so that the aircraft *i* would have the minimum separation between it and whatever the aircraft type is trailing aircraft *i.* Such a method would mean the creation of a constraint for each leading and following aircraft combination possible. This formulation modification would create a large number of constraints but may be feasible depending on the solution time of such an algorithm. More work is necessary to determine a final sequencing modification to the algorithm.

ANALYSIS OF SELECTED FORMULATIONS

While several different formulations may work for the Memphis TAA, the primary operator at Memphis, FedEx, wants to optimize their operations so that they can be as competitive as possible with any competitors within and outside the US. This requires FedEx to manage and land about 300 aircraft every night and then manage and takeoff about 300 aircraft after all the packages have been sorted and loaded back onboard all the aircraft. This occurs every night with aircraft arriving and taking off from every part of the world. Therefore, FedEx wants to test and implement the most advanced Aircraft Sequencing and Spacing algorithms in order to be the most efficient in increasing airport capacity, reduce fuel burn and emissions, and reduce noise during those peak hours. This will require formulations and cognitive engineering models that will sequence and space all arriving aircraft so that they can be on a stable glide path at the opposing merging fixes (at the edges of the TAA) and then be sequenced and spaced on the final approach segment, still on the same stable glide path, and without any additional commands or vectoring from the ATC controllers. In order for FedEx to have confidence and commit resources in this test and demonstration, the selected formulations and cognitive engineering models must also have been tested elsewhere; and verified by other users.

4a. TAA Issues and Operations at the Memphis Terminal Area

Like other TAA, the Memphis TAA can achieve tremendous benefits with a continuous stabilized arrival/approach procedure for all aircraft in the TAA that is flexible and can bend away from obstacles, thereby also reducing the landing minimums. The stabilized procedures with the constant descent profiles also supports low powered or idle engine trusts so that further benefits are achieved in fuel burn, emissions, and noise reductions. With those stabilized procedures and the aircraft sequencing and spacing formulations and cognitive engineering models, the operations at Memphis TAA can obtain benefits in the terminal area to satisfy all the objectives for this Task, as listed below:

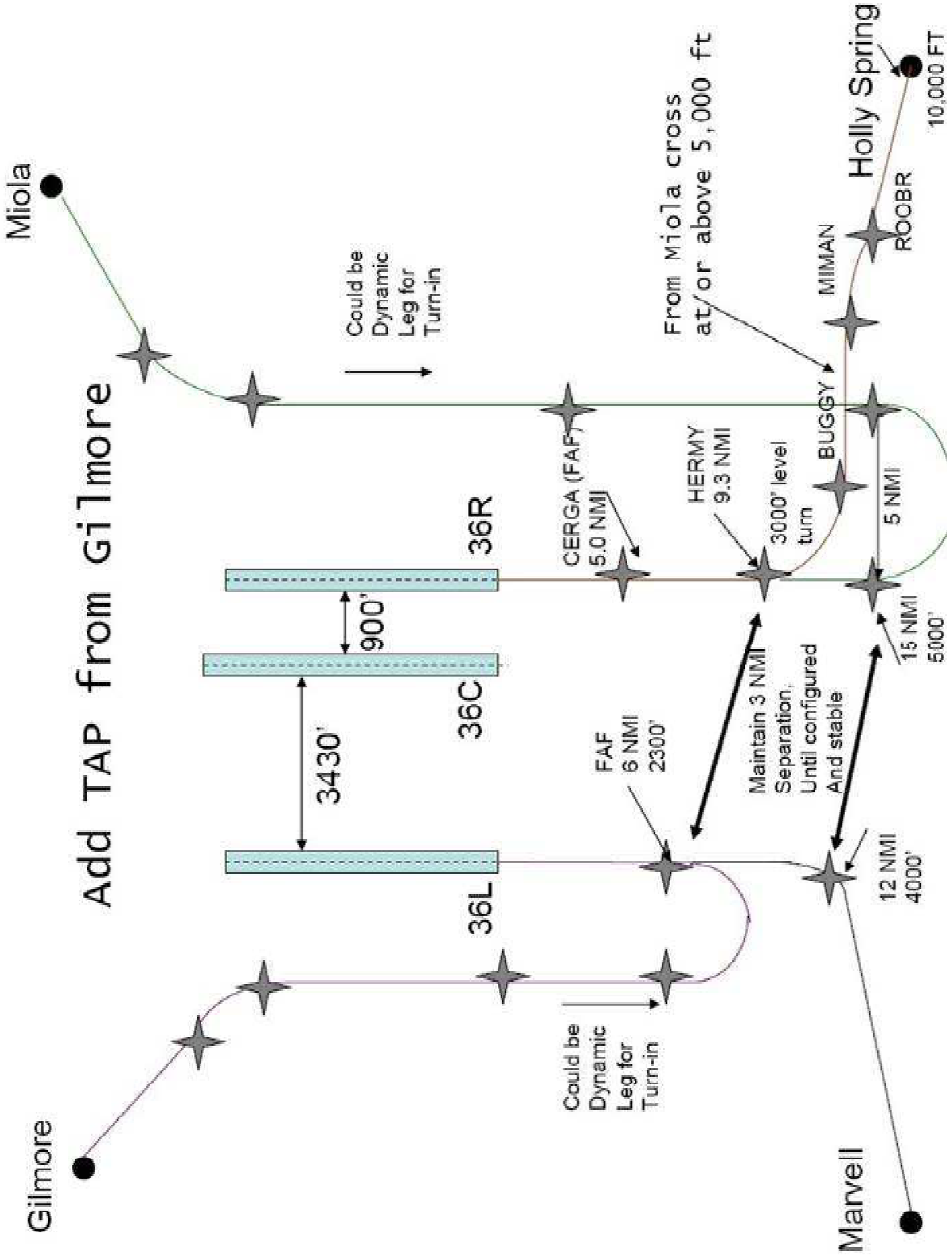
1 Decreased Fuel Burn and Emissions
2 Reduction in Noise
3 Increased Approach Availability
4 Decreased Minima where possible
5 Optimized Aircraft Sequencing in Real Time

6 Stable Arrival/Approach Procedures to Terminal Area Operations
7 Constant Rate of Descent Throughout Arrival and Approach
8 Minimized Flight Time in Terminal Area
9 Minimized Impact to ATC

The flexible stabilized arrival/approach procedures are called Terminal Area Procedures (TAP) and can be efficiency flown with a Flight Management System (FMS) in the aircraft. Therefore, with the TAP and the aircraft sequencing and spacing models, detailed radar vectoring by ATC controllers can be reduced or avoided altogether saving time and fuel. TAP procedures have been demonstrated to save about 4 minutes per approach and about 500-700 pounds of fuel depending on the aircraft type. If the TAP procedures are further started before the aircraft arrives in the TAA, then further benefits are achievable. With more accurate navigation such as the GPS or GBAS, the ground tracks are more consistent, repeatable, and precise, which may reduce obstacle clearance requirements. Sample TAP procedures have been developed for the Memphis TAA and a graphic example is shown on the next page.

In addition, FedEx also has many of the older analogue type aircraft such as the Boeing 727, which does not support the use of the digital FMS in current production aircraft. Therefore, the FAA has to demonstrate that the TAP constant descent procedures can be flown manually by pilots using only the CDI instrument deviations. This has been flight tested at the FAA Technical Centre using both government and industry pilots in an FAA Boeing 727. During those flight tests, the approach speeds, turn radius, and descent profiles were varied in order to test with the full range of flight technical errors. Those TAP procedure flight tests have been successful. Without the digital FMS, there is also a lack of a certified TAP procedure data base in the test aircraft. At the Technical Centre and at Memphis, this shortcoming can be mitigated by using the installed GBAS to broadcast the TAP procedure using the VHF Data Broadcast (VDB). The Multimode Receiver (MMR) in the aircraft can then perform the TAP procedure navigation and provide the required outputs for the analogue CDI instrument.

With the GBAS (and the VDB), the TAP procedures, and the aircraft sequencing and spacing formulations and cognitive engineering models, FedEx will be able to demonstrate all the benefits described above and improve their operations and efficiency at Memphis TAA during those peak hours at night. FedEx will also be able to demonstrate that the aircraft sequencing and spacing formulations and cognitive engineering models will be able to prioritize the landing sequence for any specific set of aircraft as determined and defined by FedEx, as long as coordination and cooperation is obtained from the FAA ATC at Memphis.


Add TAP from Gilmore
Miola
Gilmore
Marvell
Holly Spring
10,000 FT
ROOBR
MIMAN
BUGGY
From Miola cross at/or above 5,000 ft
Could be Dynamic Leg for Turn-in
Could be Dynamic Leg for Turn-in
36R
36C
36L
900'
3430'
CERGA (FAF) 5.0 NMI
HERMY 9.3 NMI
3000' level turn
5 NMI
15 NMI 5000'
12 NMI 4000'
FAF 6 NMI 2300'
Maintain 3 NMI Separation, Until configured And stable

4b. Benefits of Selected Formulations for Memphis TAA

Both the formulation described in Section 3b and the formulation described in Section 3c have been seen to work using data similar to experiences during an April 2007 flight test at Hartsfield-Jackson International Airport. Taking a sample data set of ten aircraft, scheduled to arrive at times with spacing too small to allow for a CDA procedure and solving the problem so that speed changes are given to make a CDA possible gives ATL confidence in implementing the procedures in Memphis TAA.

The following sample data is similar to situations encountered during the April 2007 flight test using Delta's aircraft. The initial conditions are described in Table 4b.1. The same initial Mach was assumed, simply to see the effects in Mach change more easily.

TABLE 4.B.1- SIMULATION STARTING CONDITIONS

Aircraft	Flight #	Type	M cruise	Flight Departure time	Initial ETA	Required Sep. (s)	Initial Sep. (s)
1	898	757-200	0.77	4:32:00 AM	8:32:00 AM	131.1	**15**
2	780	767-400	0.77	4:32:15 AM	8:32:15 AM	107.2	**135**
3	680	767-400	0.77	4:34:30 AM	8:34:30 AM	115	**60**
4	646	757-200	0.77	4:35:30 AM	8:35:30 AM	135	**160**
5	1478	757-200	0.77	4:38:10 AM	8:38:10 AM	134.8	**150**
6	1280	737-800	0.77	4:40:40 AM	8:40:40 AM	71.8	**70**
7	1240	767-400	0.77	4:41:50 AM	8:41:50 AM	137.6	**50**
8	480	737-800	0.77	4:42:40 AM	8:42:40 AM	75.2	**60**
9	1002	757-200	0.77	4:43:40 AM	8:43:40 AM	134.8	**120**
10	596	737-800	0.77	4:45:40 AM	8:45:40 AM	0	**0**

The final column in Table 4.b.1 shows the initial separation of the aircraft at the metering point. Red values indicate aircraft that would be too close to the following aircraft for them to fly the CDA procedure. The goal of the formulations described above is to provide speed changes en route to achieve the required separation calculated by TASAT and indicated in the second-to-last column of Table 4.b.1.

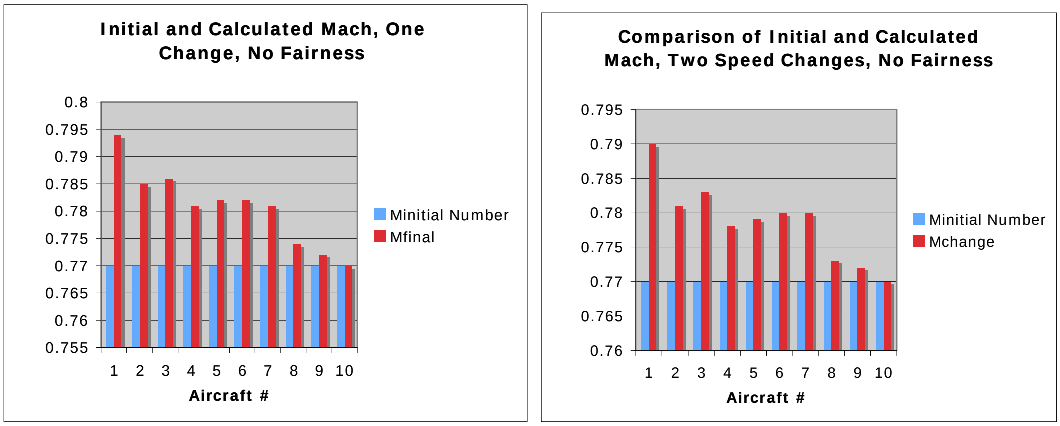


FIGURE 4.B.1-2 - INITIAL AND DESIRED MACH RESULTS, ONE-CHANGE AND TWO-CHANGE

The results in Figure 4 show compare the initial aircraft cruise Mach and the decision Mach number to which the aircraft changes speed. It is expected that the speed changes necessary in the Memphis TAA will be more drastic than those seen above. However, the formulations readily allow for such scenarios.

The next data presentation is a comparison of implementation separation times in

Table 4.b.2. Here, some of the nuances of the different solutions can be seen. Again, red values indicate aircraft that would be too close to the following aircraft for them to fly the CDA procedure. The two-change implementation spaces the aircraft closer to their minimum required separation, meaning that a maximum number of aircraft can be put in place to fly a CDA. In addition,

TABLE 4.B.2: COMPARISON OF IMPLEMENTATION SEPARATION TIMES

Aircraft	Initial Sep. (s)	Required Sep. (s)	Actual Sep. (s), One-Change	Actual Sep. (s), Two-Change
1	15	131.1	131.4	131.4
2	135	107.2	119.2	107.2
3	60	115	124.9	124.7
4	160	135	144.3	144.9
5	150	134.8	147.6	134.8
6	70	71.8	82.6	71.8
7	50	137.6	145.8	143.0
8	60	75.2	87.4	75.2
9	120	134.8	147.7	146.2
10	0	0	0	0

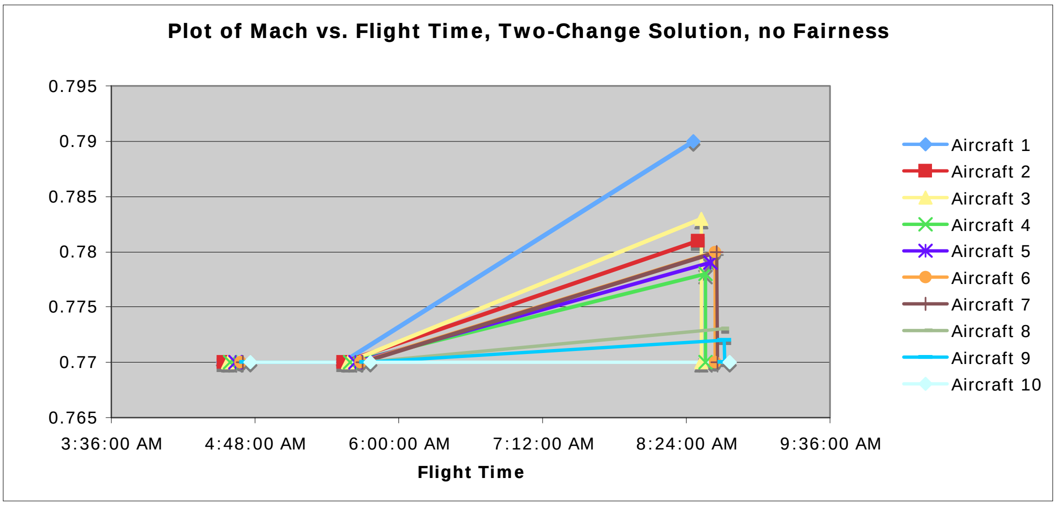


FIGURE 4.B.3- PLOT OF MACH VS. FLIGHT TIME, TWO-CHANGE SOLUTION

Finally, Figure 4.b.3 shows a schedule of when the Mach changes are made with the two-change implementation. It should be noted that while the duration of the return speed change is short, a minimum return speed segment time could be added to the formulation to make sure it is possible to make the switch.

While these initial results assume that only one aircraft stream is in place, by setting the separation times such that two streams of aircraft do not conflict on their approach, each formulation could be implemented, calculating the speed change necessary for the aircraft to fly the CDA. In addition, although the Delta aircraft involved in this flight test had FMS capabilities, the algorithm works independent of aircraft equipage, with the only requirement that the pilot be able to hold constant to the airspeed calculated. Georgia Tech's ATL will work to improve and troubleshoot the formulations in the coming months but initial results demonstrate a very feasible Memphis TAA flight test.

4c. Limitations of Selected Formulations for Memphis TAA

In devising an algorithm for a complex scenario, such as aircraft spacing for the Memphis TAA, several assumptions must be made to make the problem solvable. The important assumptions, which could impose some limitations on the application of the algorithm, are as follows:

- In all formulations, the initial speed change is made at the same time for all aircraft.
- In formulations 3c and 3d, the second speed change is always a return to the original Mach number.
- While large speed changes are allowed, the algorithm presently does not account for the time taken to accelerate or decelerate.
- Aircraft are assumed able to hold a constant airspeed.
- Multiple speed changes (more than 2) are not explicitly possible in the algorithm, although the algorithm may be solved at different instances in time as situations may change.
- Calculation of speed changes assumes wind will not drastically change for the time horizon, thus same for the new aircraft RTA. If this becomes an issue, additional speed changes might be necessary and the initial speed change would need to use a greater time buffer between aircraft.

While these assumptions are may impose limitations on the application of the above formulations, many are necessary in order to keep the problem linear, which reduces solution time, and allows for real-time implementation.

This section is also a good place to describe the future work to be undertaken in order to minimize the possible limitations. Future work will involve validating two-stream aircraft formulations, ensuring that accurate fuel burn data for all aircraft types in the flight test is available, explicitly describing a sequencing formulation, taking into account acceleration and deceleration times for large speed changes, and troubleshooting other problems as they arise before the flight test.

SUMMARY AND CONCLUSIONS

The spacing that is required at a metering point upstream of the runway to ensure (to a desired probability) that aircraft performing CDA will be conflict free will be determined for the MEM TAA using TASAT to implement the complex RNAV procedure. This methodology requires the building of a model of the winds around MEM; Monte Carlo simulation of the different aircraft types over the entire range of possible wind conditions to determine how the spacing between aircraft changes as a function of time given a particular wind condition; then the application of probability theory to determine the spacing at the metering point that ensures (to a desired probability) that the remainder of the CDA can be performed without interruption.

In addition, an algorithm has been created and will be improved upon by Georgia Tech, which sequences the landing aircraft and calculates the optimal airspeeds at which the en route aircraft must be flown to meet the necessary minimum terminal area spacing. These algorithms have been developed using data similar to a previous CDA flight test and have been shown to function as expected. In the cruise speed change algorithm's final form, it will be able to sequence multiple streams of aircraft with the allowance for two speed changes. The current limitations in the algorithm, such as accurate RTA prediction for large speed changes and sequencing ability will be addressed in the coming months.

The particular formulations described in this report—the one speed change, two speed change, and two speed change with sequencing formulations—are progressive steps toward this final algorithm to implement in the Memphis TAA. Each algorithm aims to find the minimum speed change necessary for an aircraft to arrive at a desired time, minimizing the net fuel burn for the specific aircraft type, and each is capable of being implemented in non-FMS-equipped aircraft. In addition, these algorithms have fast solution times because of the effort taken to keep the problems linear. For the ten aircraft example described in Section 4, the two-speed change solution solves in less than 1 second, using the CPLEX optimization program. The combination of fast solution times and consistency in minimizing the fuel burn for each aircraft intending to land the CDA make the speed optimization algorithms an ideal fit for the Memphis TAA program.

The goals of the MEM TAA program continue to be as follows:

- Design "static" arrival procedures that reduce noise, fuel burn, and emissions; can be flown by aircraft without an FMS; and allow for merging within the TRACON of streams from different directions destined to the same runway.
- Determine the "relative" timing between aircraft from the same or different direction so that target times for aircraft (at their corresponding metering fixes) can be determined for a given aircraft sequence; spacing between aircraft will be near the separation minimum when the leading aircraft in each pair arrives

at the runway threshold; and runway and airport arrival throughput is maximized.

- Develop sequence and spacing algorithm so that the optimal aircraft arrival sequence is determined, i.e. aircraft sequence that requires the least amount of additional fuel to achieve; target times at metering fixes and the corresponding cruise speeds required to achieve these target times are computed.
- Implement a communication system so that target times at metering fixes and cruise speeds are communicated to the aircraft.
- Implement a cockpit procedure so that each aircraft arrives at its metering fix at its target time.
- Measure aircraft performance so that noise, emissions, and fuel burn reductions can be estimated; and the spacing functionality can be evaluated.

With further development of TASAT and the speed optimization tools specific to the Memphis airspace and aircraft types involved, the above goals of the project are indeed within reach for Georgia Tech and ISI.

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[i] Clarke, J.-P. B., Ho, N. T., Ren, L., Brown, J. A., Elmer, K. R., Tong, K.-O., and Wat, J. K., "Continuous Descent Approach: Design and Flight Test for Louisville International Airport," *Journal of Aircraft*, Vol. 41, No. 5, 2004, pp. 1054-1066.

[ii] Clarke, J.-P. B., Bennett, D., Elmer, K., Firth, J., Hilb, R., Ho, N., Johnson, S., Lau, S., Ren, L., Senechal, D., Sizov, N., Slattery, R., Tong, K., Walton, J., Willgruber, A., and Williams, D., "Development, Design, and Flight Test Evaluation of a Continuous Descent Approach Procedure for Nighttime Operation at Louisville International Airport," Report of the PARTNER CDA Development Team, Report No. PARTNER-COE-2006-02, Massachusetts Institute of Technology, Cambridge, MA, Jan. 2006.

[iii] Ren, L., and Clarke, J.-P. B., "A Separation Analysis Methodology for Designing Area Navigation Arrival Procedures," *Journal of Guidance, Control, and Dynamics*, Vol. 30, No. 5, 2007, pp. 1319-1330. DOI: 10.2514/1.27067.

[iv] Ren, L., and Clarke, J.-P. B., "Flight Test Evaluation of the Tool for Analysis of Separation and Throughput," *Journal of Aircraft*, in press.

[v] Y. Lebbah, C. Michel, and M. Rueher. A Rigorous Global Filtering Algorithm for Quadratic Constraints. Constraints. 2005. Vol. 10, p. 47-65.