System Performance Characteristics of Centralized and Decentralized Air Traffic Separation Strategies

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Abstract

This work investigates the system performance characteristics of centralized and decentralized strategies for air traffic separation. A centralized separation strategy and two decentralized separation strategies, implemented as constant-speed heading-change maneuvers, were simulated for randomized horizontal traffic patterns at various traffic densities. Human decision-making of controllers and pilots were not modeled. The centralized strategy represents a controller-oriented separation system generating coordinated resolution advisories that emphasize system-level stability. The decentralized strategies represent user-oriented separation systems generating independent resolution advisories that emphasize aircraft-level efficiency. Results from numerical experiments indicate that system stability and efficiency both degrade as traffic density increases, for all separation strategies. Although decentralized separation strategies can give rise to a significant domino effect, the resulting drop in system efficiency (relative to a centralized strategy that suppresses the domino effect) is quite small for traffic densities up to a certain threshold density. Introducing even a limited stability emphasis (look-ahead capability) into the decentralized strategy can significantly reduce the domino effect and the resulting efficiency drop at very high traffic densities.

Introduction

The Distributed Air/Ground Traffic Management (DAG-TM) concept [Green et al., 2000] describes possible modes of operation within the outlines of the Free Flight concept [RTCA, 1995]. DAG-TM features distributed decision-making for Air Traffic Management (ATM) functions such as traffic separation and traffic flow management. In contrast to the current ATM system which is a centralized, ground-based positive Air Traffic Control (ATC) system, DAG-TM is an advanced ATM concept characterized by decentralized/distributed decision-making among a triad of agents: Flight Deck, Air Traffic Service Provider (ATSP), and Aeronautical Operational Control (AOC). Figure 1 illustrates the triad.

Free Maneuvering is a key element of the DAG-TM concept. Under Free Maneuvering operations, appropriately equipped aircraft may be granted the freedom to modify their trajectories in real time, while maintaining separation assurance and conforming to applicable local Traffic Flow Management constraints. In this work, we consider only separation conflicts between aircraft, and do not consider traffic flow management issues related to congested airspace, hazardous weather, Special Use Airspace (SUA), arrival metering, etc. It is noted that the Free Maneuvering element of DAG-TM primarily

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Fig. 1: The DAG-TM Triad

involves the Flight Deck and the ATSP – the AOC does not play a significant role in this element.

For the purposes of this work, system performance is characterized in terms of stability and efficiency. System stability is inversely related to the domino effect, characterized by the number of new conflicts created by conflict resolution maneuvers. System efficiency is inversely related to deviations from the nominal (user-preferred) trajectories. A significant benefit of the DAG-TM paradigm is that user-preferred trajectories can be accommodated to allow airspace users to optimize their operations. In a centralized mode of operations, the focus is typically on ATC maintaining a smooth and orderly flow of traffic, generally resulting in system stability at the expense of efficiency. In a decentralized mode of operations, users are given the freedom to optimize their own trajectories (subject to system constraints), potentially resulting in greater system efficiency. If the desired trajectories are in conflict, users have the flexibility to resolve the conflicts autonomously and efficiently, without intervention by the ATSP. A simulation study [Valenti Clari et al., 2000] reports that self-separating aircraft flying along nominal direct routes consumed less fuel than aircraft flying along structured routes (even though the structured-routing aircraft did not maneuver for separation assurance). However, under conditions of high traffic density, it is conceivable that the underlying efficiency of decentralized operations may be negated by frequent trajectory interruptions for separation assurance. The objective of this research is to determine qualitative trends in the relationship between system stability, system efficiency, and traffic density for centralized and decentralized air traffic separation strategies.

A centralized separation strategy and two decentralized separation strategies are implemented in a numerical study. The centralized strategy, representing a future ground-based separation system, is biased towards system-level stability. Both of the decentralized strategies, representing future airborne separation systems, emphasize aircraft-level efficiency; however, one is biased towards efficiency without regard for stability, while the other is permitted to give up some efficiency in order to gain some stability. All three separation strategies were implemented as constant-speed heading-change maneuvers, and repeatedly exercised in a simulation environment that generated randomized horizontal traffic patterns at various traffic densities. Human decision-making of controllers and pilots were not modeled in this study. Data from the Monte Carlo type numerical experiments were used to compute metrics for system performance in terms of efficiency and stability.

The following section addresses the modeling of system performance. Next, overviews of the algorithms used to implement centralized and decentralized separation strategies are presented. Results from numerical experiments are then presented and discussed. Finally, conclusions are drawn from the results.

System Performance Measures

The goal of this work is to determine system performance characteristics of centralized and decentralized separation strategies. System performance is measured, in terms of stability and efficiency, as a function of airspace complexity.

Stability

In this work, the concept of system stability is inversely related to the so-called "domino effect," where the process of resolving conflicts may create new conflicts with neighboring aircraft, which in turn may create additional conflicts during subsequent conflict resolutions. One possible measure of the domino effect is the incremental number of aircraft, flying along nominally conflict-free trajectories, that get drawn into conflicts by other aircraft as they try to resolve their own conflicts [Bilimoria et al., 2000]. The current work extends this measure by defining the domino effect in terms of conflict alerts. A conflict alert occurs when a separation violation is predicted over the look-ahead time horizon.

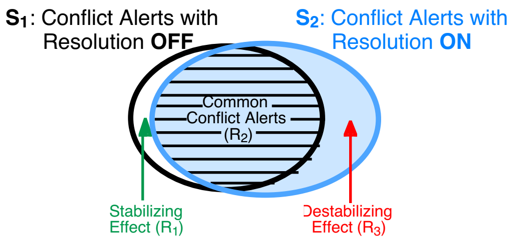

Fig. 2: System Stability Parameters

Consider a set of nominal (desired) trajectories for all aircraft in the system. In general, there will be conflicts in these nominal trajectories. The set S_1 is defined as the total number of conflict alerts that would be issued if all aircraft flew their nominal trajectories without executing any conflict resolution maneuvers. The set S_2 is defined as the total number conflict alerts that would be issued if all aircraft attempted to fly their nominal trajectories and executed conflict resolution maneuvers in response to the conflict alerts. The two sets will generally be different because the process of resolving a conflict may create a new conflict that did not exist in the nominal trajectories, and/or it may resolve a downstream conflict in the nominal trajectories.

The sets S_1 and S_2 are illustrated in Fig. 2, along with the intersecting subset R_2 and the difference subsets R_1 and R_3. The subset R_1 represents a stabilizing effect because it corresponds to alerts associated with conflicts that existed in the nominal trajectories, but did not materialize due to downstream effects of conflict resolution. The subset R_3 represents a destabilizing effect because it corresponds to alerts associated with new conflicts (not present in the nominal trajectories) caused by conflict resolution maneuvers. Noting that the domino effect is defined as a destabilizing phenomenon, the difference in the size of these two subsets, $\left(|R_3| - |R_1|\right)$, is indicative of the net domino effect on the system. The domino effect parameter (*DEP*) is defined by normalizing with respect to $|S_1|$. Hence

$$DEP = \left(\frac{|R_3| - |R_1|}{|S_1|}\right) = \left(\frac{|S_2|}{|S_1|} - 1\right) \tag{1}$$

Noting that the constant –1 in Eq. (1) above simply represents a bias element in the function *DEP*, and that there is an inverse relationship between the domino effect and system stability, a system stability metric, SS, is defined as

$$SS = \frac{|S_1|}{|S_2|} \tag{2}$$

For example $SS = 0.5$ ($DEP = 1$) indicates that the number of conflict alerts with conflict resolution ON was twice the number of conflict alerts with conflict resolution OFF.

Efficiency

For the purposes of this work, flight efficiency is the degree to which an aircraft can fly its nominal (user-preferred) trajectory. Any deviation from the nominal trajectory for conflict resolution results in an additional operational cost. System efficiency is inversely related to the system-wide average additional cost of conflict resolution.

The Direct Operating Cost (DOC) is the total cost of the time and fuel associated with a flight trajectory. Hence, the incremental DOC associated with conflict resolution is given by

$$\Delta DOC = C_{fuel}\Delta W_{fuel} + C_{time}\Delta T \tag{3}$$

where C_{fuel} is the fuel-based operating cost, ΔW_{fuel} is the additional fuel used in the conflict resolution maneuver, C_{time} is the time-based operating cost, and ΔT is the additional time used in the conflict resolution maneuver. In this work, we do not explicitly model fuel burn equations, and simply relate the cost of the additional fuel to the additional distance traveled, $\Delta\ell$, and a distance-based operating cost, C_{dist}. In our numerical experiments (described in a later section), the nominal speeds of all aircraft are identical, and the separation strategies are implemented as constant-speed heading-change maneuvers. We can therefore relate the additional time, ΔT, to the additional distance traveled, $\Delta\ell$, and the constant speed, V. Noting that $\Delta T = (\Delta\ell / V)$, and $C_{fuel}\,\Delta W_{fuel} \approx C_{dist}\,\Delta\ell$, the incremental DOC given by Eq. (3) can be approximated by

$$\Delta DOC \approx \left(C_{Dist} + \frac{C_{time}}{V}\right)\Delta\ell = K\,\Delta\ell \tag{4}$$

Since V is invariant in our numerical experiments, the quantity K in Eq. (4) above is a constant. Therefore we use $\Delta\ell$ as a proxy for ΔDOC, and define a system efficiency metric, SE, for a system of N aircraft as:

$$SE = \frac{1}{N}\sum_{i=1}^{N}\left(1 - \frac{\Delta\ell_i}{\ell_i}\right) \tag{5}$$

For example, SE = 0.97 indicates a system-wide efficiency degradation of 3%, corresponding to an average increase of 3% in trajectory length. It is noted that the average is computed across all trajectories in the system, including those that experienced no deviations ($\Delta\ell_i = 0$).

Airspace Complexity

It is evident that system stability and efficiency associated with separation assurance in some region of airspace will depend on the complexity of traffic flow across that region of airspace. Airspace complexity, also referred to as dynamic density, has been characterized by several researchers [Laudeman et al., 1998; Pawlak et al., 1996; Smith et al., 1998; Sridhar et al., 1998]. These studies indicate that there is no universal definition for airspace complexity or dynamic density. However, the number of aircraft in the airspace of interest is generally a key factor in defining airspace complexity. Other factors may include relative or absolute velocities of aircraft, as well as proximity to other aircraft, sector boundaries, SUA, storm cells, or terrain. However, all of these factors are not usually included in an airspace complexity measure.

In this study, we only utilize traffic density (number of aircraft per sq. nmi) to characterize airspace complexity at a fixed altitude. Our limited attempts to correlate more complex definitions for airspace complexity, including measures that incorporate nearest neighbor information and points of closest approach, did not provide additional insight into system performance characteristics.

Air Traffic Separation

In order to ensure safety of air traffic operations, adequate separation must be maintained. Horizontal and vertical separation requirements define a disk-shaped Protected Airspace Zone around an aircraft. A conflict occurs when an aircraft's Protected Airspace Zone is violated. For Free Flight [RTCA, 1995] operations outside of congested airspace, an aircraft is permitted to fly any desired trajectory as long as the aircraft does not actually enter the Alert Zone of any neighboring aircraft. The size and shape of the Alert Zone, which surrounds the Protected Airspace Zone, was investigated in [Krozel and Peters, 1997a; 1997b]. If an Alert Zone is penetrated and violation of its Protected Airspace Zone is predicted, the flight crews can resolve the conflict themselves while being monitored by the ATM system; in some cases an air traffic controller may intervene to solve the problem. For further information on conflict detection and resolution (CD&R), we refer the reader to [Krozel and Peters, 1997a; Bilimoria et al., 1996] for a complete analysis of conflict resolution maneuvers, considering all three control options. Also, a survey of the literature for CD&R algorithms is given in [Kuchar and Yang, 2000].

CD&R approaches generally require information on the current velocity vector of all relevant aircraft. Some approaches also require information on flight intent (e.g., next waypoint(s), top-of-climb point); this enables separation assurance over a relatively long time interval up to a maximum of about 15 – 20 minutes. CD&R approaches that utilize only current velocity vector information can reliably provide separation assurance only over short to medium time intervals, up to a maximum of about 5 – 10 minutes. In this work, we utilize only current velocity vector information, and attempt to provide separation assurance over a look-ahead time (to point of closest approach) of 8 minutes. It is acknowledged that CD&R approaches typically utilize the time to loss of separation, rather than the time to minimum separation used in this work. The impact of this difference is confined to a small subset of conflicts, characterized by shallow encounter angles and small miss distances.

Three fundamental controls for maneuvers (alone or in combination) can avoid a conflict: (1) right/left turn (heading change maneuvers); (2) accelerate/decelerate (speed change maneuvers); (3) climb/descend (vertical maneuvers). For this initial study, we consider only horizontal plane conflicts, and resolve them using only heading change maneuvers. For an isolated two-aircraft conflict, the determination of a "good" heading change maneuver for conflict resolution is quite simple and, in most cases, unique. However, if there are other aircraft in the vicinity of the two conflicting aircraft, the resolution maneuver(s) may create a domino effect which in turn may impact system performance (stability and efficiency). In this situation, the choice of conflict resolution maneuvers is influenced by the underlying separation strategy. A centralized ATC-oriented strategy will generate a set of coordinated solutions biased towards system level stability. On the other hand, a decentralized user-oriented strategy will generate a series of independent solutions biased towards aircraft-level efficiency. There are numerous possible implementations of a given separation strategy; however, the solutions generated by different implementations of the same strategy would generally exhibit similar characteristics. The remainder of this section describes the specific implementations of the separation strategies used for this study.

Implementation of Centralized Strategy

The centralized strategy implemented in this study is one possible representation of a ground-based separation strategy that could be used for future air traffic operations. For the purposes of this work, a centralized separation strategy is an ATC-oriented strategy that emphasizes the stability of the system, rather than the efficiency of individual trajectories. Coordinated resolutions are determined by a central agent that analyzes the trajectories of large groups of aircraft; these solutions are communicated to the affected aircraft that then execute the resolutions. The CD&R functions are executed periodically, corresponding to the update cycle (1 minute in our numerical experiments). Due to its strategic nature, a centralized strategy can have a cycle update rate that is significantly slower than a decentralized strategy.

The iterative "Space-Time Flow" (STF) method [Chiang et al., 1997] was implemented in our investigation, as follows. Over the course of the full simulation time, T_{SIM}, a “look-ahead window” (of length 8 minutes in our numerical experiments) is advanced in 1-minute steps, corresponding to the CD&R update cycle. Hence CD&R is performed over a series of 8-minute time windows, corresponding to the time intervals (0, 8), (1, 9), (2, 10), (3, 11), ..., ($T_{SIM} - 8$, T_{SIM}) over the duration of the simulation. At the beginning of each time window, we determine the set of conflicts that would occur in the next 8 minutes if no corrective action were to be taken. Next, we perform conflict resolution using the STF method for that 8-minute window; details are presented below. We then modify the routes accordingly, advance the 8-minute window by 1 minute, and continue.

For a given 8-minute look-ahead window, we determine conflicts that would occur during that time interval, and identify clusters of aircraft involved in these conflicts, using the conflict detection algorithm of

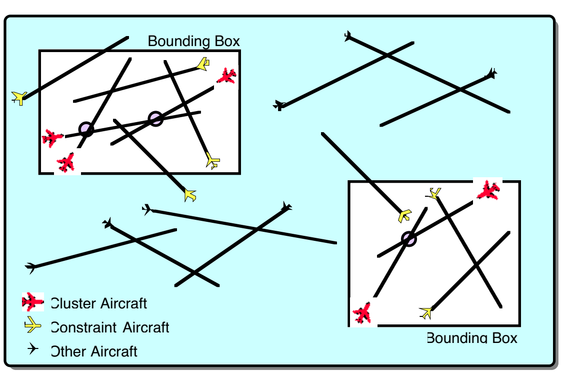

Fig. 3: Centralized Separation Strategy

[Chiang et al., 1997]. Each cluster represents a set of two or more aircraft predicted to be in conflict during the look-ahead window; e.g., if A conflicts with B, and B conflicts with both A and C (possibly at different times over the look-ahead window), then the cluster consists of A, B, and C. Next, a bounding box is constructed that contains the nominal trajectories of all the cluster aircraft over the look-ahead window; see Fig. 3 for an illustration. We then identify a set of “constraint aircraft” whose trajectories intersect the bounding box (slightly enlarged) at any time over the look-ahead window.

Within each cluster, permutation sequences are established for the aircraft; e.g., for a 3-aircraft cluster, the permutation sequences are A–B–C, A–C–B, B–C–A, B–A–C, C–A–B, C–B–A. We attempt to evaluate all permutation sequences. For small clusters, we are able to try all permutation sequences; for larger clusters of 5 or more aircraft, we consider a random set of permutation sequences, up to a maximum number of 100. In our numerical experiments, most clusters contained only 2 or 3 aircraft, and the largest observed cluster contained 10 aircraft.

For a given sequence, the first aircraft (e.g., A) is allowed to proceed without any trajectory modification. The trajectory of the second aircraft in the sequence (e.g., B) is modified using the STF method until it becomes conflict-free relative to the trajectories of aircraft A and all constraint aircraft associated with the cluster. We then proceed to the next aircraft in the sequence (e.g., aircraft C), and modify its trajectory until it becomes conflict-free relative to the trajectories of aircraft A, aircraft B, and all constraint aircraft associated with the cluster. We attempt to continue in this fashion along the permutation sequence. If the search ever fails to find a conflict-free route for the next aircraft in a permutation, we deem that permutation to have failed, and consider other permutations. If conflict-free routes are found for all aircraft in a permutation sequence, then that cluster is done, and we proceed to the next cluster. If we fail to find a permutation that allows us to resolve a cluster, then we permit the CD&R algorithm to utilize a small number of “bad” aircraft routes corresponding to those aircraft for which no feasible route was found. Each bad aircraft is routed according to its original trajectory (which leads to conflicts with other cluster aircraft). In this case, we select that permutation which leads to the fewest such bad aircraft routings. An overview of the STF method is presented below.

The STF method treats the conflict resolution problem as that of constructing a feasible set of non-intersecting “pipes” (representing aircraft trajectories that have been offset to account for the separation standard) in the space-time domain. The nominal trajectories of constraint aircraft are inserted as obstacles prior to the incremental insertion of modified trajectories of the cluster aircraft. For each cluster aircraft, we search for a feasible route for its "pipe," subject to the space-time obstacles represented by the existing pipes (already inserted as obstacles in the space-time domain) of the constraint aircraft and all previous cluster aircraft in the permutation sequence. The goal is to preserve system stability to the extent possible, by disallowing conflicts of the new routes of cluster aircraft with the existing routes of constraint aircraft. The STF method attempts to construct a conflict-free trajectory by searching for a new waypoint that will be inserted into the current trajectory (if this results in a large angular deviation, the STF algorithm attempts to insert an additional waypoint, up to a total number of 7 waypoints). The search is conducted in a way that favors shorter feasible paths.

Implementation of Two Decentralized Strategies

The decentralized strategies presented here are possible representations of cockpit-based separation strategies that could be used for Free Maneuvering operations. For the purposes of this work, a decentralized separation strategy is a user-oriented strategy that emphasizes the efficiency of individual trajectories, rather than the stability of the system. Each aircraft resolves its own conflicts as they are detected, over a "look-ahead window" (of length 8 minutes in our numerical experiments). The CD&R functions are executed periodically, corresponding to the update cycle (1 second in our numerical experiments). A conflict is "detected" if it is predicted to occur with a time to closest approach value of less than 8 minutes. If an aircraft detects conflicts with more than one aircraft within the 8-minute window, it resolves them in a sequential pair-wise fashion; at each CD&R update cycle, only the most immediate (minimum time to closest approach) conflict is resolved, until all conflicts are solved. The aircraft resumes a course to its next waypoint when there are no conflicts within the look-ahead window. The CD&R algorithms of [Krozel and Peters, 1997a and 1997b] were implemented in our investigation. Only constant-speed heading change maneuvers are utilized in this implementation.

Two types of decentralized strategies are considered in this work: Myopic and Look-ahead. Figure 4 illustrates these conflict resolution approaches. For heading change maneuvers, there are two solutions (frontside and backside) that can provide a resulting minimum separation distance equal to the horizontal separation standard. The "myopic" decentralized strategy determines the most efficient resolution for the conflict at hand, choosing and executing the maneuver (frontside or backside) that requires the least amount of heading change. If this maneuver creates a new conflict, it is resolved at the next CD&R update cycle.

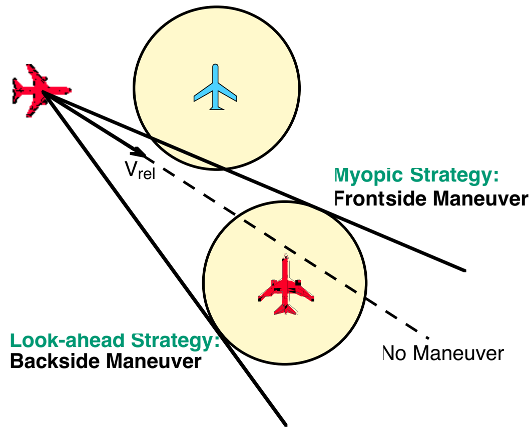

Fig. 4: Decentralized Separation Strategies

The "look-ahead" decentralized strategy first determines the more efficient maneuver (frontside/backside), and then checks if this maneuver would create a new conflict with time to closest approach value less than that of the original conflict. If no such conflict is found, it executes the more efficient maneuver (yielding the same solution as the myopic strategy). However, if such a new conflict is found, it checks the other (backside/frontside) solution to see if a conflict-free path is available; if so, it executes that solution. If not, it searches for conflict-free paths, starting from the original (more efficient) frontside/backside solution, using heading change increments of 2 deg, until a conflict-free path is found. We note that in this case, the resulting minimum separation distance relative to the original conflict aircraft will be greater than the horizontal separation standard.

There is a difference between the two decentralized strategies. The myopic decentralized strategy executes the most efficient resolution (for an individual conflict), without considering any adverse impact this maneuver may have on system stability (resulting from the creation of new conflicts). On the other hand, the look-ahead decentralized strategy has the flexibility to trade-off some efficiency in return for some stability, enabling it to mitigate the domino effect.

Numerical Experiments

Simulation Environment

A constant-speed horizontal-flight simulation model was used to exercise the centralized and decentralized separation strategies, implemented as described in the previous section. The simulation included a simple model of turn dynamics. It is noted that conflict resolutions executed with a lead time of 5 – 10 minutes typically require only a few degrees of heading change, which can be executed in a few seconds.

All aircraft in the simulation were constrained to fly level at the same altitude, with a constant speed of 500 knots. The aircraft were randomly routed through a 100 nmi radius circular test airspace modeling a "super sector" of high-altitude en route airspace in a future operational environment. Random routing is used as a first approximation in this study, while noting that it may not be an accurate representation of actual Free Flight routing patterns that would depend on city-pair locations, wind fields, airspace restrictions, and user preferences. The simulation is set up to approximate a constant density traffic flow. As the simulation progresses, new aircraft are initiated to replace aircraft that are terminated when they reach the end of their routes.

As shown in Fig. 5, the test environment is defined by two concentric circular sets of 100 waypoints (evenly spaced 3.6 deg apart). The inner circle of 100 nmi radius represents the test airspace, and the outer circle creates a 20 nmi buffer around the test airspace. An aircraft is assigned a nominal route that starts at a random waypoint on the outer circle and terminates at a random waypoint on the inner circle (this ensures that new aircraft will not be initiated in conflict with existing aircraft in the test airspace).

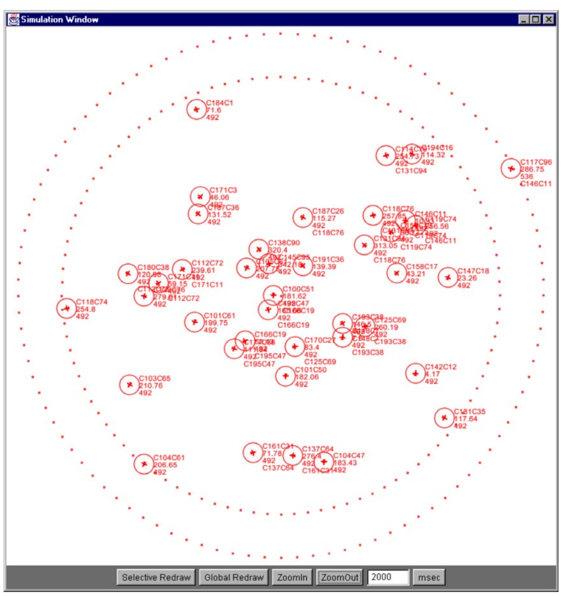

Fig. 5: Simulation Environment

Data Collection

Numerous Monte Carlo-type data collection runs of 3,000 seconds (50 min) each were made, as described below. The instantaneous count of simulated aircraft ranged from 5 to 80, in increments of 5 aircraft, over the reference area defined by the inner (100 nmi radius) circle. The corresponding 16 traffic densities ranged from approximately 1 to 25 aircraft per 10,000 sq. nmi.

In order to provide some perspective on density values, U.S. Center-wide densities over several 2,000 ft airspace strata centered at high flight levels (above FL 290) were determined from a 24-hour recording of real traffic data. The peak U.S. Center-wide densities ranged from approximately 1 to 5 aircraft per 10,000 sq. nmi, depending on the Center. It is noted that local densities in small regions of airspace within a Center could be significantly higher.

18 traffic scenarios were generated for each of the 16 values of traffic density, resulting in a total of 288 different scenarios. Each traffic scenario corresponds to a different randomized set of aircraft birth times, birth points, and nominal routes. Four simulation runs were made for each of these 288 traffic scenarios: a nominal case with no separation assurance, a case with the myopic decentralized separation strategy, a case with the look-ahead decentralized separation strategy, and finally, a case with the centralized separation strategy. Each separation strategy attempted to provide at least 5 nmi of horizontal separation between all aircraft. Data on conflict alerts and path lengths were recorded, and the stability and efficiency metrics given by Eqs. (1), (2) and (5) were computed. Some data on separation violations was also collected.

Results and Discussion

The number of separation violations was generally small relative to the total number of conflicts existing in the nominal (CD&R off) traffic scenarios, and increased with traffic density. However, a piloted simulation study of decentralized separation assurance [Hoekstra et al., 2000] has determined that safety can be maintained even at high traffic densities, up to 3 times current average Western European values. Therefore this work does not further analyze separation failure rates, but focuses on system performance in terms of stability and efficiency.

Figures 6 through 9 illustrate the relationship between stability, efficiency, and traffic density, for the separation strategies implemented in this work. It is noted that all the trends observed in these figures arose naturally from a large set of randomized traffic scenarios that represent operations in a future free-routing environment. From the results, it is clear that an increase in traffic density degrades both the stability and efficiency of all three separation strategies, i.e., the two decentralized strategies and the centralized strategy.

Figs. 6 and 7 present the domino effect parameter (*DEP*) given by Eq. (1), and the system stability metric (*SS*) given by Eq. (2), respectively, as functions of traffic density. It is noted that $DEP = 1/SS - 1$; hence Figs. 6 and 7 show the same data, but from inverse perspectives. It is observed that the system stability is directly related to the level of emphasis placed on stability by the separation strategy, as expected. At each data point for traffic density, the centralized strategy has higher stability (lower domino effect) than either of the two decentralized strategies; also, the look-ahead decentralized strategy has higher stability (lower domino effect) than the myopic decentralized strategy. It can be seen that the centralized strategy suppresses the domino effect over the entire range of traffic densities investigated. At the lowest traffic density used in the study (about 1.5 aircraft per 10,000 sq. nmi), the two decentralized strategies yield essentially the same level of domino effect, because the look-ahead decentralized solution is generally the same as the myopic decentralized solution when there is very little traffic in the vicinity of conflicting aircraft. Across the two decentralized strategies, the differences in domino effect are quite small up to a density of about 5 aircraft per 10,000 sq. nmi; beyond this density there is a strong divergence.

Fig. 8 presents the system efficiency metric (*SE*) given by Eq. (5), as a function of traffic density. It reveals a complex relationship between system efficiency and traffic density for the three separation strategies. It is noted that even a 0.01 change in the efficiency metric (corresponding to a 1% change in system-wide direct operating cost) is considered to be quite significant from an operational perspective. For densities of up to 12 aircraft per 10,000 sq. nmi, both of the decentralized strategies yield greater efficiency than the centralized strategy. At all densities above 14 aircraft per 10,000 sq. nmi, the centralized strategy is more efficient than either of the two decentralized strategies. For densities in excess of 16 aircraft per 10,000 sq. nmi, the look-ahead decentralized strategy is more efficient than the myopic decentralized strategy, but is still less efficient than the centralized strategy;

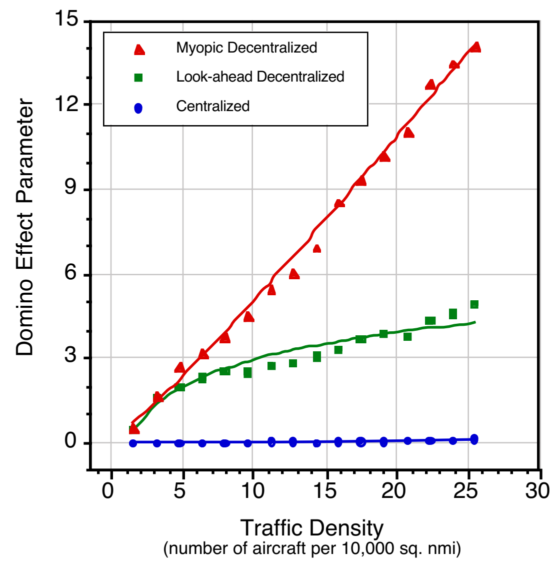

Fig. 6: Domino Effect vs. Traffic Density

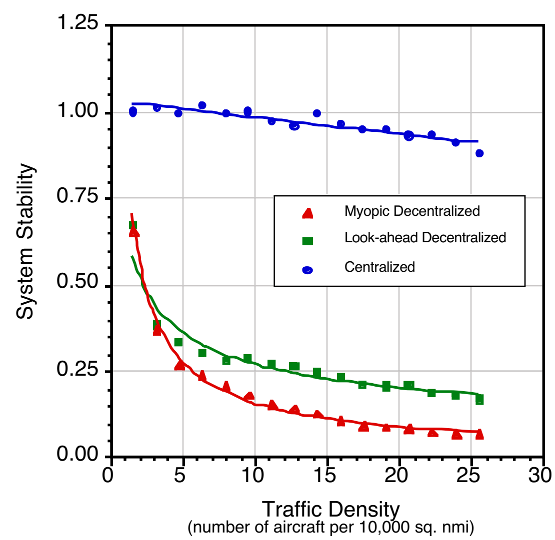

Fig. 7: System Stability vs. Traffic Density

this trend persists over the remaining range of data points for our numerical experiments, up to a density of approximately 25 aircraft per 10,000 sq. nmi. It is noted that the differences in efficiency across the three separation strategies are not very significant for traffic densities less than about 15 aircraft per 10,000 sq. nmi.

The above observations on the data presented in Figs. 6 – 8 lead to some interesting insights on the relationship between stability and efficiency across the three separation strategies. Under the myopic

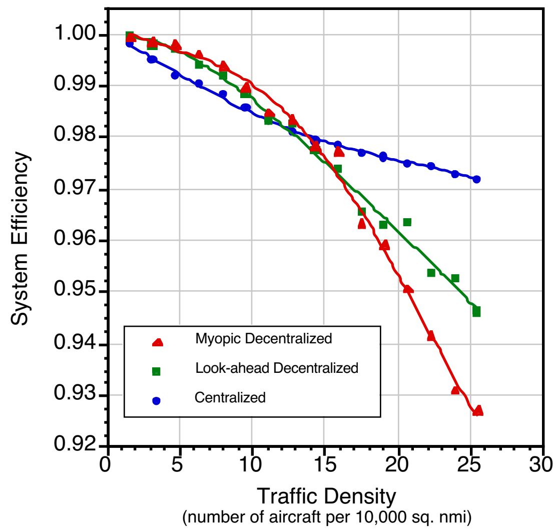

Fig. 8: System Efficiency vs. Traffic Density

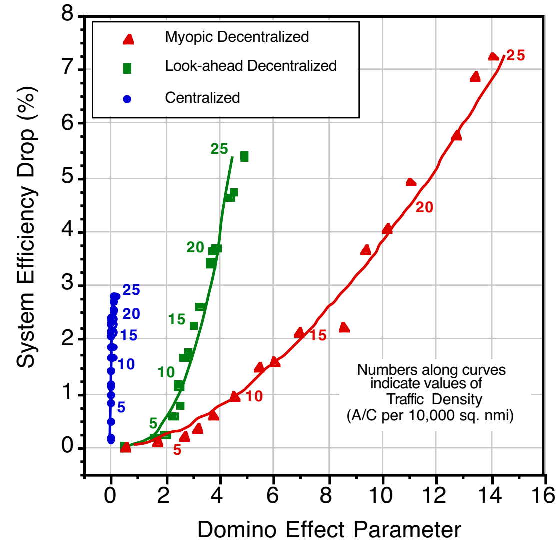

Fig. 9: Efficiency Drop vs. Domino Effect

decentralized strategy, conflict resolutions focus exclusively on efficiency; aircraft resolve their most immediate conflicts in a way that minimizes deviations from the nominal trajectory, without regard for stability. This strategy works well up to a certain threshold density (roughly 15 aircraft per 10,000 sq. nmi in our numerical experiments) because although the domino effect can be quite strong, new conflicts arising from the domino effect can be resolved without an excessive penalty on system efficiency. On the other hand, the centralized strategy focuses primarily on stability by avoiding the creation of new conflicts with neighboring aircraft, even at the expense of larger trajectory deviations. Relative to the myopic decentralized strategy, the centralized strategy yields higher stability at the expense of lower efficiency, for densities up to the threshold value mentioned above. The look-ahead decentralized strategy lies somewhere between the centralized and myopic decentralized strategies; while it focuses primarily on efficiency, it is allowed to trade-off some efficiency to gain some stability. Hence, the stability and efficiency characteristics for this strategy also lie somewhere between the other two strategies.

Beyond the threshold density, an increasingly powerful domino effect imposes an increasingly large penalty on efficiency for both of the decentralized strategies. Focusing exclusively (or primarily) on efficiency for the resolution of the most immediate conflict results in a very large number of new conflicts created by the domino effect; resolving these conflicts gives rise to substantial system-wide incremental costs ($\Delta DOC \approx \Delta\ell$) which significantly degrade system efficiency. The centralized strategy may not resolve each individual conflict as efficiently as the decentralized strategies, but it comes out ahead at the system level at very high densities (above roughly 15 aircraft per 10,000 sq. nmi in our numerical experiments) because it creates substantially fewer new conflicts by suppressing the domino effect.

Fig. 9 shows the system efficiency drop $(1 - SE)$ as a function of domino effect parameter at each of the traffic densities used in the numerical experiments, for all three separation strategies. This figure, which is essentially a composite of Figs. 6 and 8, highlights the relationship between stability and efficiency across the three separation strategies (as implemented in this work). System performance should be compared across the separation strategies only at corresponding traffic density data points on the curves.

Conclusions

System performance characteristics of centralized and decentralized separation strategies were investigated at various traffic densities, using Monte Carlo type simulations to generate randomized horizontal traffic scenarios. System performance metrics for stability and efficiency were defined. The centralized separation strategy was oriented towards stability, and the two decentralized separation strategies were oriented towards efficiency. These separation strategies were implemented in the simulation as constant-speed heading-change maneuvers. Human decision making (pilots and controllers) was not modeled. The following conclusions were drawn from the results of the numerical experiments; it is noted that they reflect the scope and assumptions of the study. The emphasis is on qualitative trends, rather than numerical values.

The centralized strategy is generally able to preserve system stability by suppressing the domino effect at all traffic densities studied, but the associated system efficiency degrades with increasing traffic density. For the two decentralized strategies, system stability and efficiency both degrade with increasing traffic density. Significant nonlinearities were observed in these relationships. Although characterized by different biases towards stability and efficiency, all three separation strategies yield essentially the same system efficiency at very low traffic densities, with only small differences in domino effect. Across the separation strategies, significant differences in domino effect appear and grow as traffic density increases, but the differences in system efficiency remain small for densities up to about 15 aircraft per 10,000 sq. nmi in our numerical experiments. Beyond this threshold density, there are significant differences across the separation strategies in both domino effect and system efficiency.

These results support the feasibility of airborne (decentralized) separation assurance for Free Maneuvering operations in a DAG-TM environment. The data indicate that although decentralized separation assurance can give rise to a significant domino effect, the resulting drop in system efficiency (relative to a centralized strategy that suppresses the domino effect) is not very large for traffic densities less than a threshold value. Introducing even a limited stability emphasis (look-ahead) into a decentralized strategy can significantly reduce the domino effect and the resulting efficiency degradation at very high traffic densities. The results of this study indicate that mitigation of the domino effect should be an important consideration in the design of algorithms for future airborne separation assurance systems operating in very high density environments.

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