Flight Deck-Based Merging and Spacing during En Route Descent: Findings from an Air Traffic Controller Simulation

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Abstract— **In an effort to achieve consistent, low variance spacing between aircraft pairs during arrival operations and to reduce aircraft maneuvering, noise, fuel burn, and controller workload, the Federal Aviation Administration (FAA) is developing, and UPS has implemented an Automatic Dependent Surveillance-Broadcast (ADS-B) concept termed Merging and Spacing (M&S). M&S has two phases: a strategic set-up by a ground operator followed by tactical Flight Deck-Based Merging and Spacing (FDMS). In the initial implementation, both phases, involve pilots being requested to fly speeds from sources other than Air Traffic Control (ATC). In FDMS, the speeds are generated and displayed on-board the aircraft via a Cockpit Display of Traffic Information (CDTI) or other displays. The flight crew follows those speeds to achieve and maintain a desired time interval from a lead aircraft.**

This paper focuses on FDMS and presents the subjective and objective results of a human-in-the-loop simulation that examined the concept from the en route controller perspective during an in-trail operation, from aircraft top-of-descent through entry into terminal airspace in a Continuous Descent Arrival (CDA). Termed FDMS 4, the simulation was conducted in May and June of 2007 and is part of a development and maturation process that is underway for FDMS. The impact of FDMS on controller operations during entry to a CDA, as well as human performance, operational impact, and communications issues were examined. Concept acceptability and the handling of non-normal situations were also evaluated.

Controllers reported on average that FDMS during en route descent operations was acceptable, desirable, and an improvement in operational efficiency. FDMS allowed for acceptable workload and traffic awareness – even in the event of spacing disruptions. Controllers had no issues intervening with FDMS traffic when necessary; however, controller responses were varied on whether it was acceptable to give FDMS aircraft priority. FDMS helped reduce overall controller interventions in an arrival stream under normal conditions, but did not increase or decrease total interventions for overall sector traffic sets under normal conditions or when spacing disruptions were introduced.

I. INTRODUCTION

Noise and environmental impacts of air travel are major concerns for aviation, especially for airports and those living nearby. Additionally, fuel costs have become a major concern of airlines as the price of petroleum reaches record highs. More efficient arrival procedures, sometimes referred to as Continuous Descent Arrivals (CDAs), can help offset some of these issues. CDAs are a specific form of Standard Terminal Arrival Route (STAR). They typically start in the en route environment and are designed to keep aircraft at higher altitudes longer and reduce noise, emissions, and fuel burn by decreasing or eliminating level off segments and the associated thrust transitions. The arrivals are designed to allow aircraft to meet required speed restrictions (e.g., 250 kts below 10,000 feet) and to allow for a stabilized final approach [1]. CDAs can be defined such that the arrival joins the instrument approach procedure without requiring the Air Traffic Control (ATC) vectoring seen with conventional arrivals.

Before joining a CDA, aircraft arriving at an airport typically originate from numerous departure points and traverse different routes prior to merging into an arrival stream. This convergence is often necessary for an orderly delivery to the arrival and approach, and is accomplished through merging at downstream en route or terminal area waypoints. In order for the merge to be successful, aircraft on the routes to be joined must be synchronized in time and have sufficient spacing to allow for other aircraft to fit into the overall flow while maintaining, at least, the minimum required separation between aircraft.

In order to realize the full benefits of a CDA, aircraft must be able to fly the arrival with minimal deviations from the route or other controller interventions. Miles-in-trail (MIT) or metering restrictions (meter fix times) are typically put in place to absorb delays when the downstream sector or an airport is

predicted to be or is currently congested due to conditions such as weather or the volume of traffic [2]. However, they can also be used to allow aircraft to meet spacing requirements between aircraft pairs prior to flying the arrival. When MIT operations are in effect, ATC must merge the flows and maintain the separation standards while maneuvering the aircraft to meet the restrictions from downstream sectors.

Traditionally, spacing is not achieved during the en route phase of flight prior to top of descent. Controllers currently lack the appropriate tools to efficiently plan the flow into the terminal area across multiple centers. If spacing cannot be achieved early on in the flight and MIT restrictions are in place, vectors are typically used to adjust in-trail spacing or to avoid conflicts since speed changes are often inadequate to affect the spacing within the sector [3]. Instead of being able to direct an aircraft to maintain a specific in-trail spacing interval, controllers must provide specific instructions, or instruction sequences, in order to achieve their goal. This process can be workload intensive for controllers and pilots and can also increase fuel consumption and flight time.

In the United States (US), the FAA is developing, UPS has begun implementing, and Aviation Communication & Surveillance Systems (ACSS) is building equipment to support an ADS-B concept termed Merging and Spacing (M&S). M&S is intended to allow flight crews, ATC, and airlines to efficiently achieve and maintain a desired spacing between aircraft pairs from the en route phase of flight down to the runway threshold. The goal of the initial implementation is to avoid downstream vectoring and speed changes by having the Airline Operations Center (AOC) set up spacing among chains of paired aircraft early on in the flight, and then to give flight crews the ability to maintain their spacing using on-board equipment through the arrival and approach in a manner consistent with today's Instrument Flight Rules (IFR) procedures and criteria.

The initial UPS planned implementation of M&S is occurring in a low density, late night environment and is comprised of two phases: a strategic ground setup phase and a tactical flight deck phase. The first phase is termed Airline Based En-Route Sequencing and Spacing (ABESS) [4]. It consists of the AOC using a new tool to determine the desired sequence and spacing at a common merge fix for its arrival flow. Once the sequence and spacing intervals are determined, the AOC sends speed advisories to company aircraft via the Aircraft Communications Addressing and Reporting System (ACARS) that flight crews will follow to achieve the desired goal. As the flight crew approaches the merge fix, the AOC will then uplink an advisory that includes, at minimum, the Traffic To Follow (TTF) flight identification, the spacing interval in seconds, and the common merge waypoint for the aircraft pair. After the flight crew inputs this information into the on-board systems, the operation can transition to the second phase, designated as Flight Deck-Based Merging and Spacing (FDMS).

FDMS allows for more active flight crew participation in achieving the desired spacing interval of an AOC and ATC. The main objective is to achieve consistent, low variance spacing between paired aircraft during arrival operations

through flight deck-originated speed adjustments. It uses on-board equipment to calculate and display information that allows the flight crew to manage their speed to achieve a desired spacing interval at and beyond a common merge fix. Speed changes are exclusively used to achieve the desired spacing; use of vectoring or heading changes via flight deck equipment is not part of this initial FDMS implementation. Pairs of FDMS aircraft can be formed into linked chains by allowing a trailing aircraft in one pair to be a TTF for its following aircraft, provided that all aircraft in the chain are appropriately equipped.

M&S is expected to provide several benefits for airline operators, air traffic managers, and controllers. When an airline can use minor speed adjustments to ensure consistent and predictable spacing, controllers should be able to reduce the number of interventions they need to make with the traffic. Reduced maneuvering saves the airlines time and fuel, and should also reduce controller workload. Fewer necessary controller interventions should also result in fewer calls to aircraft, which lessens the load on the communications frequencies. If M&S helps controllers handle the current traffic streams more efficiently, they may be able to handle additional aircraft in their sector and airspace capacity could potentially be increased.

FDMS is also beneficial during CDA operations in medium density airspace. CDAs allow aircraft to maximize their individual efficiencies; however, this can come at the expense of the efficiency of the overall stream. By having aircraft manage their own spacing, FDMS allows aircraft conducting CDAs to effectively balance individual and stream efficiency, and act in a manner beneficial to the overall system.

To take advantage of these benefits, UPS has begun to implement FDMS for aircraft flying from the Western US into its main hub at Louisville International Airport – Standiford Field (SDF). UPS currently has its Boeing 757 / 767 fleet equipped with ADS-B and Cockpit Display of Traffic Information (CDTIs) for traffic awareness [5]. FDMS builds on this current equipage by adding new applications and displays that allow more efficient and consistent CDA operations.

M&S is being matured in an FAA-sponsored development group that is supported by organizations such as the FAA, UPS, ACSS, Boeing, Honeywell, National Aeronautics and Space Administration (NASA), Eurocontrol, MITRE, and others. To support this effort, MITRE is executing a series of human-in-the-loop simulations to evaluate this initial implementation from the perspectives of pilots and controllers, in both the en-route and terminal domains. The first two simulations, FDMS 1 and FDMS 2, evaluated the operation during an en-route merge operation from the ATC and flight deck perspectives, respectively. The third human-in-the-loop FDMS simulation, termed FDMS 3, evaluated the impact of FDMS on the flight deck during arrival (specifically a CDA) and approach operations under both normal and non-normal conditions. All three simulations found general acceptability and improvements over current-day operations under normal and non-normal conditions. In comparison to current-day operations, FDMS 1 showed a reduction in: the number of controller-issued maneuvers, the number of communications,

and workload. A reduction of situation awareness was not observed. Some variability existed as to issues related to monitoring and interventions [6, 7].

The FDMS 2 and FDMS 3 pilot participants in general reported that FDMS: was acceptable, was compatible with current operations, had no adverse impacts on workload or situation awareness, and allowed for a reduction in communications with ATC [8, 9, 10, 11]. However, they raised some concerns about a retrofit CDTI location and the integration of that display in their scan, and some participants in the third simulation reported increased acceptability of FDMS when the CDTI location was moved to the primary field of view

This paper summarizes the major findings from a fourth simulation, termed FDMS 4, which examined FDMS from the en route controller perspective during the arrival from the top of descent (TOD) to handoff to the terminal area. It examined the concept under both normal and non-normal conditions as defined in the most current version of the application description, which was [12] (note that a newer version of this document based on continued work is available as [13]). Whereas FDMS 1 examined the ATC en route merge environment, FDMS 4 was specifically concerned with the post-merge and arrival. A more complete description of the major findings of the FDMS 4 simulation is available in [14].

II. FDMS OPERATIONAL CONCEPT

To establish a hierarchy for applications fielding and to help define the tasks and responsibilities of pilots and ATC, a joint US and European group [15] developed four categories for Airborne Surveillance Applications (ASA): Airborne Traffic Situation Awareness, Airborne Spacing, Airborne Separation, and Airborne Self-Separation. FDMS has been developed as an Airborne Spacing application, which requires flight crews to "achieve and maintain a given spacing with designated aircraft…Although the flight crews are given new tasks, separation provision is still the controller's responsibility and applicable separation minima are unchanged" [15]. This differs from Situation Awareness applications where pilots are simply using the CDTI to enhance their understanding of the traffic picture. It also differs from Separation applications, where separation responsibility is transferred from ATC to the flight deck. Later implementations of FDMS may involve such a transfer, but Spacing applications are expected to be more appropriate for initial implementations.

FDMS builds on similar concepts being explored in other research facilities such as Eurocontrol (as CoSpace [16]), NASA Langley (as Airborne Merging and Spacing for Terminal Arrivals (AMSTAR [17]), and NASA Ames (as Trajectory-Oriented Operations with Limited Delegation (TOOWiLD) [18]). These concepts have a more active ATC role, but are very similar to FDMS from a flight deck perspective. The international Requirements Focus Group (RFG) is also defining a similar concept termed Enhanced

Sequencing and Merging [19].

A. Conduct

FDMS begins when aircraft are merging at a common fix in the en-route environment, having been previously sequenced and spaced by the ABESS setup phase. Prior to the merge fix, the AOC delivers the FDMS initialization advisory via ACARS. The AOC can initially be the entity providing this information, since the test environment is late night / low complexity and consists mainly of UPS aircraft. Later implementations in higher density environments will require ATC to deliver this information.

Once received, the flight crew inputs this information into their on-board systems, engages FDMS, and then receives the first FDMS speed command (CMD) via a CDTI or other display. Flight crews follow the CMDs to achieve the desired spacing interval at the merge fix and then maintain that interval until approximately the final approach fix. At this point, CMDs are no longer provided and the flight crew continues to configure normally and slow to the final approach speed.

Pairs of FDMS aircraft can be formed into linked chains by allowing a trailing aircraft in one pair to be a TTF for its following aircraft, providing all aircraft in the chain are appropriately equipped. There can be breaks in the chains of aircraft conducting FDMS (Figure 1) and other non-participating aircraft can be managed with conventional ATC methods

B. ATC Responsibilities and Procedures

The initial FDMS implementation is designed to be as transparent as possible to ATC. Controllers will be informed when FDMS is being conducted, but are not expected to need to know details such as specific aircraft pairings and target spacing intervals. As with [1], they should not require any new tools to facilitate the operation.

The controller's responsibility for separation does not change when FDMS is being conducted. ATC will monitor and maintain separation for all aircraft at all times. As they do normally, they will receive and, if appropriate, clear the flight crews for any heading or speed requests. ATC will not give specific clearances for FDMS but will for the routing and arrival procedures.

The spacing interval targeted by FDMS aircraft should approximate the interval desired by the controller prior to handoff to a downstream sector as well as that needed in the terminal area and upon landing. If the ATC-required spacing is different from that being provided by FDMS, controllers will intervene as they do today to achieve their desired spacing. ATC-initiated speed or heading instructions essentially stops FDMS for those aircraft. If the aircraft is able to resume its speed or rejoin the routing of other FDMS aircraft, FDMS could be re-initiated. The specific conditions and procedures for this case are still under development.
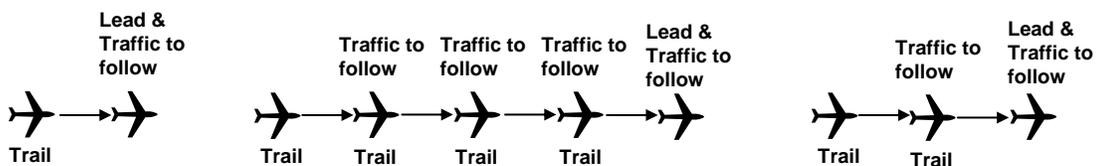
Figure 1. Sample Stream of Aircraft Conducting FDMS with Breaks in the Chains

ATC will be expected to prevent non-participating aircraft from interfering with FDMS operations to the extent possible. For example, if a controller desires to resolve a situation between two aircraft and does not have a clear preference for which aircraft path to modify, the controller would be expected to intervene with the non-FDMS aircraft. ATC is also expected to avoid instructions contradictory to FDMS operations, unless necessary. For example, ATC would not be expected to offer routing that conflicts with the FDMS routing, e.g., ATC should not offer direct routing to shorten the defined arrival procedure. In order for ATC to fulfill these desired outcomes, it will need to have an understanding of the goals and desires for FDMS operations.

III. SIMULATION DESCRIPTION

In order to help mature FDMS prior to implementation, MITRE developed and executed an en-route ATC simulation that involved FDMS and non-FDMS streams of traffic cleared for arrivals under normal and non-normal situations. The simulation was also designed to provide an early examination of some of the potential benefits of FDMS and address operational issues as the concept moves through development and fielding. In particular, the simulation addressed ATC acceptance as well as the impact on operations, workload, situation awareness, and communications. FDMS is expected to have the following impact:

- Reduction in controller workload based on aircraft self-delivering a spacing interval (as with [6 and 21])

- Reduction in the number of controller interventions based on aircraft self-delivering a spacing interval (as with [6, 22])

- No impact on controller situation awareness even though the aircraft are self spacing without controller instructions

- Reduction in the amount of monitoring required (as with [21])

- Reduction in the number of communications due to reduced ATC interventions (as with [23])

- No impact on the safety of current operations (as with [1 and 23])

A. Method

1) Simulation Environment: The simulation was hosted at the MITRE Air Traffic Management (ATM) laboratory. The main simulation functions included an en-route controller workstation and a traffic generator. The workstation included current ATC equipment: a Display System Replacement (DSR) with keyboard, trackball, and Display Interface Keypad (DIK), as well as a second display that hosted the User Request Evaluation Tool (URET). No new controller tools were implemented for the evaluation.

A second station hosted the pseudopilot and a software program that allowed for the entry of instructions from ATC. Pseudopilot inputs modified the behavior of aircraft that otherwise were following generated flight plans. A MITRE individual acted as the pseudopilot that "flew" all the aircraft. The traffic generator hosted a MITRE-developed version of the EUROCONTROL algorithm [24], which provided CMDs directly to the FDMS aircraft[1]. Pseudopilots saw the CMDs for the aircraft they were controlling, but did not need to take action for those speeds to be sent to the aircraft. A custom interface allowed the pseudopilot to override the algorithm and input speed or other instructions from ATC. The controller and pseudopilot stations were located in separate areas and communications were provided via headsets.

2) Airspace: The simulation examined the portion of the route in Indianapolis Center (ZID) airspace between the merges at Centralia (ENL) and Farmington (FAM) and the Louisville TRACON. As is done in the field during a late night operation, the high and low altitude sectors were combined, which resulted in only one controller participant being necessary to work the traffic flow between Kansas City Center (ZKC) and the Louisville TRACON terminal area. Participants were instructed to hand off traffic to Louisville TRACON when they passed through 14,000 ft

3) Arrival Traffic: Two arrival streams entered the participant's sector. The BGEST traffic stream contained both FDMS capable and non-capable aircraft, and consisted of eight B767 and six B757 aircraft that merged at ENL and were cleared by ZKC for the BGEST ONE CDA to 35L. The PXV traffic stream contained only FDMS non-capable traffic, and consisted of four A306s and one DC8 aircraft that merged at FAM and were cleared by ZKC for the PXV ONE CDA to 35R. The UPS aircraft flight identifications were varied between the scenarios to try to reduce practice effects.

In order to evaluate a sufficiently mature FDMS implementation, while at the same time investigating some of the impacts of operating in a mixed-equipage environment, it was decided that the simulation should assume that roughly 75% of the BGEST traffic stream should be capable of FDMS. As a result, of the 14 aircraft making up the BGEST ONE stream, eleven were considered to be FDMS capable. Furthermore, to account for the possibility of upstream sectors cancelling spacing, some of the FDMS capable aircraft were not actively spacing. However, other aircraft could space off of them, so the presence of the leads accounted for this possibility. The arrival traffic could thus be classified into three different types: FDMS lead, FDMS spacing, or non-participating. Following the convention shown in Figure 1, each was defined as:

- *FDMS lead*: an aircraft that could potentially space off of the aircraft ahead of it, but was not. However, it served as the TTF for the aircraft behind it.

- *FDMS spacing*: an aircraft that was spacing off of the aircraft ahead. If no aircraft was spacing off of it, it could also be classified as a "trail". For simplicity, this paper usually refers to these aircraft as "self-spacing".

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[1] As the simulation focused mainly on conceptual and human performance issues, no attempt was made to validate the performance of the speed guidance implementation used in the experiment against the performance of other, validated implementations.

- *Non-participating*: aircraft that were neither self-spacing, nor being spaced off of.

Several characteristics of the arrival flows were varied within and between scenarios in order to create events called for by specific scenarios (i.e. overtakes), and vary the traffic between scenarios to reduce practice effects. Each characteristic is described below:

a) Setup error: Each scenario assumed an ABESS initial spacing setup for the arrival flows; however, some scenarios attempted to model varying setup qualities. In general, aircraft entered the participant controller's sector already in trail, but not always perfectly spaced. The trailing FDMS aircraft were assigned a Spacing Interval (SI) of 150 seconds behind their TTF, except in the case of a 757 following a 767 which maintained a 180 sec SI. It was assumed that FDMS aircraft spacings at the merge fix would contain some error relative to the assigned intervals. These error values, on either side of the interval, were distributed more or less randomly to the individual aircraft within the FDMS chains.

b) Chain configuration: Within the FDMS stream, 11 of the 14 aircraft (including leads) were part of FDMS chains, each of which contained between two and four total aircraft (including the lead). This resulted in scenarios having between three and five chains per flow, with three non-participating aircraft randomly interspersed. Chain configurations were usually randomly assigned; however, some scenarios required particular configurations.

c) Initial gap: The initial spacing gap sizes between chains of aircraft was designed to be larger than, the same as, or smaller than the intervals that would be assigned if the aircraft were spacing behind a TTF. Aircraft speeds were assigned such that the gaps were either quickly or gradually closing or opening, or stable. Gap size and behavior was also distributed somewhat randomly throughout the scenarios.

d) Descent angles. In order to minimize the number of speed commands received by the flight deck, the FDMS concept calls for FDMS aircraft to pass through the same windfields during the descent. This results in each aircraft having the same top-of-descent (TOD) point and path angle. However, other aircraft on the CDAs would be free to choose their own TOD points which results in a variety of descent points and descent path angles throughout the stream.

To account for this in the simulation, the aircraft descent angles varied within the streams: all FDMS TTFs and trails had a common descent angle within a scenario (although they were varied between scenarios), but the angle of the non-FDMS aircraft was varied by +/- 1 degree. This resulted in varying TOD points along the route; some aircraft entered the participant's sector already descending and some began their descent after entry. The participant was notified, however, that all aircraft were cleared for descent by ZKC. The initial altitude was always FL350 for the FDMS traffic; the non-FDMS traffic entered either at FL330 or FL350, or FL310.

4) Crossing Traffic: Several non-UPS flights also passed through the ZID sector and some presented conflicts with the arrival streams. The crossing traffic routes and identifications were derived from real-world traffic flows at the time the FDMS operation is expected to occur. The times that the crossing flights entered the sector were kept constant; however the varying arrival times of the BGEST and PXV aircraft created variability in the timing of the conflict resolutions across scenarios which helped reduce the potential for practice effects across the scenarios.

5) Participants and Procedure: Eight en route controllers and supervisors participated in the simulation. Two of the en route participants were former R controllers with recent experience. The other six were from two other Centers. All were males with a mean experience level of 20 years.

The simulation period lasted two days for each participant. Each simulation day lasted 8 to 9 hours, and the same procedures were used each time. Upon arrival, controllers were given a 1 hour introductory briefing that covered the concept, workstation, airspace, traffic, algorithm, phraseology, and procedures. Controllers were instructed that their tasks were to ensure spacing and separation and minimize disruptions to the FDMS stream to the extent possible.

After the brief, controllers were brought into the lab and presented with a series of six training scenarios designed to introduce them to the workstation, FDMS under normal conditions, and some of the off-nominal events that could occur during FDMS. After the training, controllers were presented with nine scenarios in which objective and subjective data were collected: two scenarios the first day, and seven the second day. The order of the data collection scenarios was randomized in order to minimize any learning effect bias. Subjective data was gathered in the form of post scenario questionnaires, a final questionnaire, and a final debrief given at the end of the second day. Objective data was collected automatically.

B. Scenarios

The conditions were scripted such that all simulation events occurred within the participant's sector. Each scenario started with the initial aircraft in the BGEST traffic stream just east of ENL, and ended when the participant instructed the last BGEST arrival aircraft to "contact Louisville Approach." Scenarios generally lasted about 45 minutes.

All FDMS scenarios had a corresponding baseline scenario. The traffic for each FDMS+Baseline scenario pairing started with the identical parameters; however, in the baseline scenarios call signs were changed between pairs and the traffic did not receive speed commands from a spacing algorithm (i.e., the spacing algorithm did not assist controllers in maintaining a spacing outside of their MIT restriction). Additionally, no deliberate disruptions were presented in the baseline scenarios.

The tasks of the algorithm and controller were slightly different. The controller had a miles-in-trail restriction of 10 mi at the BGEST fix, which was inside of the assigned FDMS spacing intervals. Controllers were instructed that although they had to meet a spacing restriction, they were not expected to close gaps to meet a spacing interval. This is desirable since controller interventions by definition stop the FDMS procedure, which may lead to additional interventions downstream. The algorithm, however, was attempting to achieve a particular spacing value.

The following sections describe the specifics of the scenarios used in the evaluation. Scenario event summaries are provided in Table I.

1) FDMS Normal: The normal operations scenario was intended to evaluate FDMS operations under relatively benign conditions, i.e. without the deliberate introduction of FDMS spacing disruptions or other problems. Controllers were asked to ensure 10 MIT by BGEST for the UPS 757 / 767 traffic; however, the algorithm made it unnecessary for the controllers to have to provide instructions to the FDMS spacing aircraft to achieve the MIT. The controller did, however, have to resolve the occasional conflict between BGEST and PXV arrival traffic and non-participating aircraft.

2) FDMS Call Sign: The call sign scenario was intended to test whether additional information about the FDMS operation would be necessary for controllers during check in. These scenarios were the same as the FDMS Normal scenario in that FDMS proceeded without incident, and there was no deliberate introduction of spacing disruptions or other problems. However, the call sign scenarios introduced a phraseology variant in which pilots indicated whom they were spacing off of. In this case, pseudopilots indicated their TTF by using the following phraseology on check in: "*Indy Center, UPS[XXX] with you on the BGEST, company spacing off UPS[ZZZ].*" In all other FDMS scenarios pseudopilots checked in aircraft that were actively spacing using only the phrase: "*UPS[XXX] with you on the BGEST, company spacing.*"

3) FDMS Poor Delivery: The poor delivery scenario was designed to evaluate a situation in which the FDMS setup was not performed as effectively as intended and aircraft pairs were still attempting to achieve spacing well after the merge fix. Pairs entered the participant's sector either inside of their SIs with FDMS spacing aircraft trying to slow to achieve spacing, or the SI had not been achieved by the merge fix and FDMS spacing aircraft had higher airspeeds in order to catch up. Although the aircraft entered the sector in trail, the gaps between aircraft were either closing or opening at greater rates than in the normal scenarios.

4) FMDS Termination: The termination scenario started with nominal FDMS conditions. However, a situation was assumed that required all aircraft to stop FDMS and return to baseline conditions. When most of the FDMS aircraft were well within the sector boundary, the simulation director made the following statement to the controller: "*This is your supervisor. UPS is stopping all company-spacing operations. You've now got spacing responsibility for everybody in your sector. Your 10 mile, miles-in-trail restriction is still in place. UPS has conveyed this to their pilots, so you don't need to notify them.*"

5) FDMS Disruption: The disruption scenario also started with all aircraft successfully performing FDMS. It contained, however, three events which introduced disruptions to the FDMS operation. Two involved aircraft following the wrong TTFs, which was designed to test the ability of controllers to detect this error and also how they might correct the situation. In both cases, the first roughly 12 minutes from the start, the second roughly 35 minutes from start, FDMS spacing aircraft were flying maximum forward speeds in an attempt to catch up

with their (erroneous) TTFs. This created overtake situations that the controller had to detect and resolve. If the controller queried why their speeds were so high, the pseudopilots were instructed to answer: "*I'm following the speed commands given on my equipment. Everything appears normal.*" If controllers asked the trails whom they were following, the pseudopilots were instructed to respond with the call sign of the aircraft ahead of the aircraft they should have been following. If the controller did not act to resolve the situation, the spacing aircraft would have been inside of the MIT restriction with its TTF at the BGEST fix.

The other event involved an aircraft disengaging FDMS approximately 14 minutes from the scenario start using the phraseology call: "*Indy Center, UPS916. Terminating Company Spacing.*" The aircraft stayed on the arrival and after seven more minutes, announced it was resuming company spacing by using the phraseology: "*Indy Center, UPS916. Company Spacing.*" This event was included to examine how controllers would manage aircraft that changed their FDMS status, as well as a preliminary evaluation of phraseology.

TABLE I. SCENARIO SUMMARY

Scenario Name	No FDMS Operations	No Deliberate FDMS Disruptions	Third Party Call Sign Use	Deliberate Poor Set Up	All Aircraft Terminate FDMS at same Time	Aircraft follows wrong TTF	Aircraft Disengages / Re-engages FDMS
FDMS Normal		X					
Baseline Normal	X						
FDMS Call Sign		X	X				
FDMS Poor Delivery		X		X			
Baseline Poor Delivery	X			X			
FDMS Termination					X		
Baseline Termination	X						
FDMS Disruption						X	X
Baseline Disruption	X						

IV. RESULTS AND DISCUSSION

Numerous subjective and objective data metrics were collected during the experimental runs. Subjective data was gathered via questionnaires and the debrief, which included topics such as workload, situational awareness, acceptability, roles and responsibilities, and communications. Most questions were on a seven point scale while other questions were yes /

no, open ended, or on another scale. Participants were encouraged to add detail in open text fields to justify or clarify their answers. The questionnaires were built based on past research on and testing of ADS-B applications.

Objective data parameters were recorded either via the traffic generator, the algorithm host, the cockpit host, or the audio recorder. Recorded items included aircraft state data, commanded aircraft trajectory change counts and magnitudes (heading, speed, altitude, crossings reroutes), and audio metrics. After the runs, the raw objective data was reduced, checked for errors, and summarized for later statistical analysis.

For statistical tests, the difference between means for an effect was considered significant if it has a *p*-value less than or equal to 0.05 ($p \leq 0.05$). Any effect with a *p*-value less than or equal to 0.01 ($p \leq 0.01$) was considered significant while those between 0.01 and 0.05 were considered marginally significant. Effects with *p*-values greater than 0.05 ($p > 0.05$) were not considered significant.

A. Concept

Overall, controllers found the FDMS operation to be generally acceptable, desirable, and an improvement in operational efficiency. One dissenting controller felt that FDMS was only compatible with ATC operations into an airport like SDF, but still found the concept to have merit. They also generally agreed that the FDMS spacing was acceptable and that spacing being achieved by FDMS aircraft approximated the spacing they desired. However, controllers on average somewhat disagreed that it was acceptable to expect them to give priority to aircraft conducting FDMS over non-FDMS traffic for conflict management. Those that gave reasons reported that they wouldn't unless there was an operational advantage to them and that safety and separation are always the highest priority. One controller noted that although he wouldn't otherwise, he might give priority if the stream was solely UPS aircraft, and that was what UPS wanted.

All controllers, on average, agreed that their roles and responsibilities were clear. All controllers agreed that they were comfortable intervening with aircraft performing FDMS and that FDMS interventions are an acceptable part of the concept. Most controllers reported not treating the FDMS aircraft differently from the other aircraft in the arrival stream. For those that did, they felt the treatment had a positive effect. On average, controllers did not find it difficult to know when to intervene when aircraft were conducting FDMS. However, there was some variability in the answers with one controller noting that it could be difficult to know when to intervene in the situations when an aircraft is conducting FDMS with the wrong TTF.

All controllers were able to manage the FDMS off-nominal scenarios. All controllers agreed or completely agreed that the situations where aircraft had to terminate FDMS were acceptable. They also all agreed or strongly agreed that it was acceptable for flight crews to declare and re-engage FDMS off the same aircraft. Most also agreed that it was desirable for pilots to be able to re-engage FDMS off the same aircraft, but two were borderline.

B. Impact on Operations

1) Analysis Description: The objective intervention data was examined to determine whether FDMS introduced any differences in the number of controller interventions by scenario. All of the analyses evaluated total interventions, which were a combination of heading, speed, and altitude instructions to aircraft. FDMS and corresponding baseline scenarios were paired into four groupings for the operations analysis: Normal+Call Sign; Poor Delivery; Termination; and Disruption. Since different traffic sets were used between scenario groupings to minimize practice effects, comparisons between other pairs do not allow for a determination of whether the significant results observed would be due to differences in the scenario variables or whether the differences would be due to variations in the traffic sets. As such, this analysis is organized by the scenario groups, with comparisons and discussion between the groups only as appropriate.

Five main sets of analyses were performed for each of the scenario groups. A summary of the aircraft categories included in each analysis is presented in Table II, and descriptions of each analysis follows the table. A run order analysis was performed for each analysis type for each scenario group, and no statistically significant results were observed. This suggests that the results were not confounded by participant learning.

TABLE II. AIRCRAFT TYPES INCLUDED IN EACH ANALYSIS

Analysis	Leads	Self-Spacing	BGEST Non-Spacing	PXV Arrivals	Crossing Traffic
Self-Spacing Only		X			
BGEST Non-Spacing	X		X		
All BGEST	X	X	X		
All Non-BGEST				X	X
All Traffic	X	X	X	X	X

Self-Spacing Only: Examined whether FDMS affected controller intervention rates for the self-spacing (FDMS spacing) aircraft. The FDMS concept, as defined by [12], suggests that controllers should give priority to FDMS aircraft − particularly those on an arrival path. Participants in the simulation were briefed that in the event of a conflict or spacing problem between an FDMS and non-spacing aircraft, they were to try to resolve the problem by giving instructions to the non-spacing aircraft.

The spacing analyses test whether there was a difference in the number of interventions given to spacing and non-spacing aircraft in the same positions in the baseline/FDMS scenario pairs. Since each baseline/FDMS scenario pair started with the same traffic in the same state, the total intervention counts for the same aircraft in the scenario pairs could be compared. For example, in the spacing analyses if the Xth aircraft in the arrival stream was actively conducting FDMS, controller interventions for that aircraft, and its corresponding aircraft in its baseline, were included in the analysis.

BGEST Non-Spacing: Examined whether FDMS resulted in an increase or decrease in controller interventions with the BGEST non-spacing traffic. The non-spacing arrival aircraft equivalents in the baseline were derived in the same manner as in the Self-Spacing analysis: if the Xth aircraft in the BGEST arrival stream was *not* actively conducting FDMS, controller interventions for that aircraft, and its corresponding aircraft in its baseline, were included in the analysis

All BGEST: Examined the effect of FDMS on controller intervention rates with a mixed-equipage arrival stream of self-spacing aircraft. The BGEST arrival flow was analyzed to explore differences in controller interventions with a mixed-equipage arrival flow of self-spacing aircraft. It examined the effect of FDMS on an overall arrival stream, and whether any benefits from any observed decreases in intervention rates with FDMS aircraft were nullified by overall increased interventions rates elsewhere in the stream.

All Non-BGEST: Examined whether the presence of FDMS aircraft on a CDA affected the number of interventions elsewhere in the sector. The non-BGEST traffic was examined separately to determine whether there was any carryover effect from an FDMS CDA stream to the rest of the aircraft in the sector.

All Traffic: Examined the effect of FDMS on controller intervention rates for the entire sector. This was intended to ensure that any differences caused by FDMS in the way that controllers interacted with the entire traffic picture were accounted for. It was also intended to examine whether any benefits from any observed decreases in intervention rates with FDMS aircraft were nullified by overall increased interventions rates elsewhere in the sector.

2) Normal + Call Sign Results: The analyses in this section compared the Baseline Normal and FDMS Normal scenarios to examine the impact of FDMS on a traffic set that was properly spaced and sequenced by the merge fix. The FDMS Call Sign scenario shared the traffic set, and thus was also included in the analysis to determine if introducing the TTF's call sign into the check-in communication had any effect on controller intervention rates. The mean data for the total intervention types are presented graphically in Figure 2.
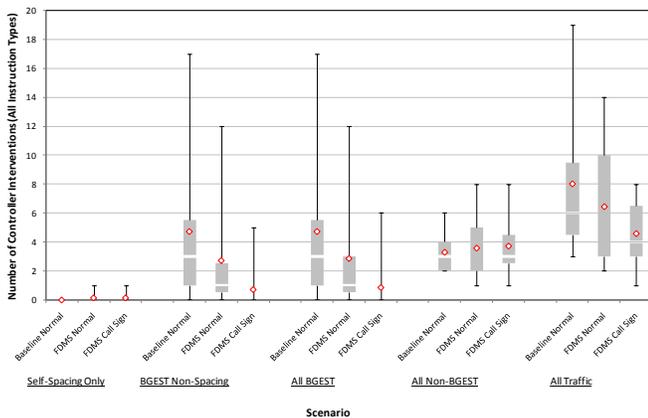
Figure 2. Controller Mean Total Interventions: Normal+ Call Sign

Normals: Paired comparison *t*-tests were run between each of the scenarios in each analysis set in order to determine where any significant differences occurred. No significant differences in total controller interventions were found between the Baseline Normal and FDMS Normal scenarios for the self-spacing aircraft. However, the disparity in the number of controller interventions between the self-spacing and non-spacing traffic in both the Baseline Normal and FDMS Normal scenarios suggests the importance of proper sequencing / spacing setup over the merge fix.

Since the overall intervention rates for the spacing aircraft and baseline equivalents were near zero, few controllers found it necessary to intervene with the spacing aircraft and equivalents on the BGEST CDA. However, controllers did make several interventions with the non-spacing arrival traffic in both scenarios. In the traffic setup, the non-spacing arrival traffic were often deliberately assigned initial speeds that would create minor overtakes with the aircraft ahead of them. This was done to create realistic variability in the spacing between FDMS chains. However, these scenarios also assumed that the arrival traffic was set up for success by a ground tool or upstream controller. To replicate this, the initial speeds of the self-spacing aircraft were usually more closely matched within the chains than those of the non-spacing arrivals. Since the same initial traffic conditions were used for both scenarios, the initial baseline speeds for the spacing aircraft equivalents were close enough to provide acceptable spacing throughout the arrival. This suggests that for a properly setup arrival stream, FDMS may not be as large of a factor as proper sequencing/spacing setup over the merge fix in reducing controller interventions during the initial stages of the descent.

For the BGEST Non-Spacing case, controllers made significantly *fewer* total interventions with the BGEST non-spacing traffic (leads, non-participants) in the FDMS Normal scenario than they did in the Baseline Normal scenario ($p = 0.038$). The same effect was observed when analyzing all traffic in the stream (ALL BGEST: spacing, leads, non-participants; $p = 0.045$). This suggests that FDMS can help to reduce interventions in an overall arrival stream, even if the effect is not seen for the spacing aircraft themselves. This could be due in part to at least two effects: first, it might have increased some self-spacing aircraft speeds such that the degree of overtake with non-spacing aircraft was reduced to the point at which controllers found it unnecessary to intervene. Second, it might also have increased the controller's overall comfort level with the stream such that the controller didn't feel the need to "fine-tune" the spacing. A reduction in interventions was not observed for the overall sector traffic, however, which suggests that the effect may be limited and can be reduced as the overall traffic picture increases in complexity.

There was no difference between the Baseline Normal and FDMS Normal scenarios in the Non-BGEST analysis, which suggests that the presence of FDMS had little effect on the number of controller interventions with the other aircraft in the sector (PXV arrival and crossing traffic).

FDMS Call Sign: The BGEST Non-Spacing ($p = 0.045$) and All BGEST ($p = 0.039$) analyses showed significant reductions in controller non-spacing aircraft interventions in

the Call Sign scenarios over the Baseline Normal scenario. However, since they also found significant differences between the Baseline and FDMS Normal scenarios, and no significant differences were observed between the FDMS Call Sign and FDMS Normal scenarios in those analyses, it is likely that the significance of Call Sign in reducing interventions is due more to the presence of FDMS than the introduction of the third-party flight identification.

However for the All Sector Traffic case, there was no observed significant reduction in interventions between the Baseline and FDMS Normals. This suggests that the reduction in interventions as a result of introducing FDMS can be diluted as the traffic situation increases in number and complexity (or more aircraft need to be performing FDMS to observe significant reductions in controller interventions across all sector traffic). But a significant reduction in interventions was observed between Baseline and Call Sign for the All Traffic case ($p = 0.043$), which indicates that the introduction of Call Sign may increase the effectiveness of FDMS in reducing the controller intervention rate.

3) Poor Delivery Results: The analyses in this section compared the Baseline Poor Delivery and FDMS Poor Delivery scenarios to examine the impact of FDMS on a traffic set that was still attempting to achieve spacing after the merge fix and into the descent. The mean data for the total intervention types are presented graphically in Figure 3.
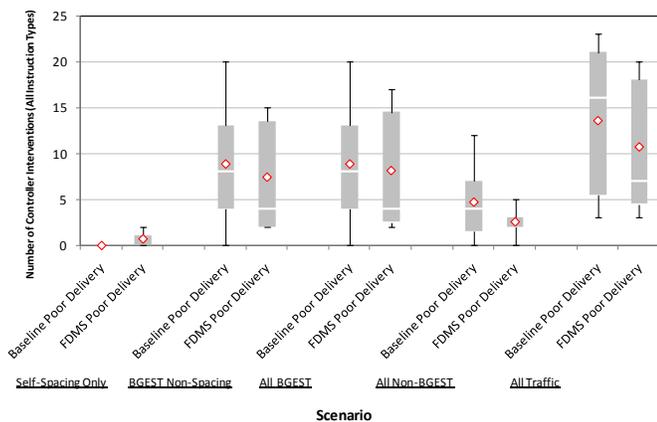
Figure 3. Controller Mean Total Interventions: Poor Delivery

Paired comparison *t*-tests were run between each of the scenarios in each analysis in order to determine where the significant differences occurred. For the self-spacing only group, there were significantly *more* interventions in the FDMS Poor Delivery scenario than there were in the Baseline ($p = 0.047$). One possible explanation for this is that when resolving conflicts, controllers intervened primarily with spacing aircraft in the FDMS scenarios, but then primarily intervened with the non-spacing aircraft equivalents in the baseline scenarios. To investigate this possibility, further intervention analyses were performed to determine whether there were differences in intervention rates when factoring in the non-spacing arrival traffic.

No significant difference was observed between the two poor delivery scenarios in the BGEST Non-Spacing aircraft

analysis. This suggests that controllers did actually intervene more often with the self-spacing traffic in the FDMS Poor Delivery scenario, as opposed to shifting the interventions from non-spacing to spacing aircraft. As a result, the addition of FDMS actually increased the overall number of interventions in this traffic set.[2]

One possible explanation for this is that since the FDMS algorithm was still working to fix the spacing, controllers may have had some uncertainty as to whether the algorithm would achieve the spacing in time to meet their MIT restriction. As a result, they may have decided to intervene early to eliminate their uncertainty. Since there were no interventions in the Baseline scenario, they maintained spacing responsibility for the traffic at all times, and thus may have been more inclined to wait to intervene.

Although the spacing aircraft analysis found an increase in controller interventions when FDMS was introduced in a poor delivery environment, no significant change in total interventions was observed in any of the other analyses. So when viewed from an arrival stream or all sector traffic perspective, FDMS neither reduced nor increased the controller intervention rate for an overall arrival stream that is still trying to achieve spacing into the descent.

4) Termination Results: The analyses in this section compared the Baseline Termination and FDMS Termination scenarios to examine the impact of FDMS on a traffic set that Terminated FDMS after several self-spacing aircraft were already in the controller's sector. The mean data for the total intervention types are presented graphically in Figure 4.
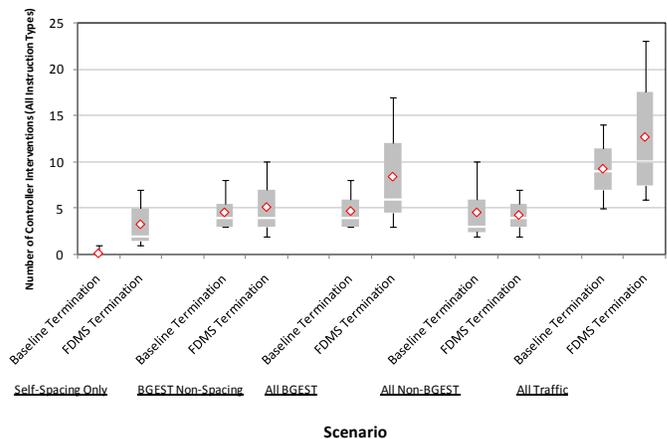
Figure 4. Controller Mean Total Interventions: Termination

Paired comparison *t*-tests were run between each of the scenarios in each analysis in order to determine where the significant differences occurred. The results show that for the self-spacing aircraft, controllers made significantly *fewer* total interventions in the Baseline Termination scenario than they did in the FDMS Termination scenario ($p = 0.023$). One possible explanation for this is that when resolving conflicts, controllers intervened primarily with spacing aircraft in the

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[2] An increase in FDMS interventions was also seen for the following Termination and Disruption cases, and the same analysis was run which produced the same effect.

FDMS scenarios, but then primarily intervened with the non-spacing aircraft equivalents in the baseline scenarios. As with the previous case, an analysis of the BGEST Non-Spacing aircraft suggests the addition of FDMS did result in an increase in the overall number of interventions for this traffic set.

Since there was no significant difference in the Baseline Normal/FDMS Normal intervention rate for the self-spacing traffic, it appears that as long as it was functional, controllers trusted the algorithm to maintain spacing. Additionally, controllers were generally satisfied with the spacing aircraft traffic picture in the Baseline Termination scenario as evidenced by the minimal interventions. Thus, the likely key driver for the increase in spacing aircraft interventions with FDMS was its termination. Controllers felt that they had to intervene after FDMS terminated to ensure the MIT restriction would be met. This could indicate that controllers did not maintain as strong SA of the spacing aircraft when FDMS was active, and may have felt that they needed to actively intervene to manage the spacing when FDMS terminated. In reality, few of these interventions were needed as the aircraft would have properly maintained the MIT at the BGEST fix, even if there were no additional controller interventions.

No significant difference in intervention rates was observed for any of the other analyses. From the perspective of the arrival and overall traffic picture, controllers neither intervened more nor less when FDMS was terminated, which suggests that the effect was weak and any decrease in SA was minimal.

4) Disruption Results: The analyses in this section compared the Baseline Disruption and FDMS Disruption scenarios to examine the impact of FDMS on a traffic set that contained self-spacing aircraft overtakes and aircraft disengagements. The mean data for the total intervention types are presented graphically in
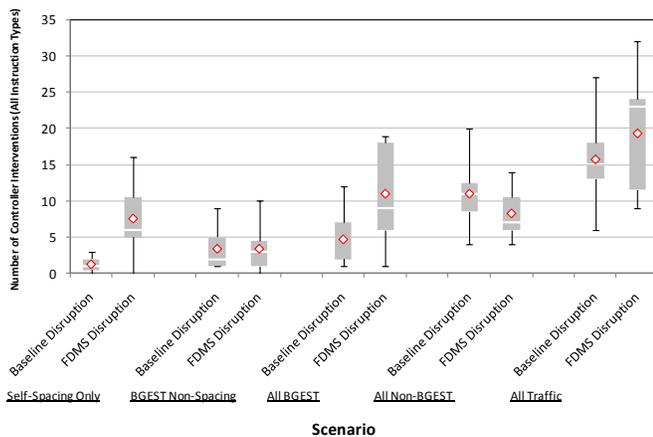
Figure 5. Controller Mean Total Interventions: Disruption

Paired comparison *t*-tests were run between each of the scenarios in each analysis in order to determine where the significant differences occurred. Significantly *more* self-spacing aircraft interventions were found in the FDMS Disruption scenario than in the Baseline ($p = 0.019$). One possible explanation for this is that when resolving conflicts, controllers intervened primarily with spacing aircraft in the

FDMS scenarios, but then primarily intervened with the non-spacing aircraft equivalents in the baseline scenarios. As with the previous case, an analysis of the BGEST Non-Spacing aircraft suggests the addition of FDMS did result in an increase in the overall number of interventions for this traffic set.

This is not unexpected, as the FDMS Disruption scenario involved deliberate overtakes (trails following wrong TTFs) that the controller had to resolve. Although artificial speed changes that were made to accomplish the goals of the scenario were not included in the intervention counts, controllers' responses to them were. The baseline spacing aircraft started from the same position, but were not driven into an overtake situation. The same effect was observed for the overall BGEST stream ($p = 0.031$), but not for all traffic. This suggests that although FDMS disruptions may increase interventions for an arrival, its influence decreases as the traffic picture increases in complexity.

C. Communications

On average, controllers felt that FDMS somewhat reduced communications that they had with the traffic, as compared to controlling a similar number of aircraft under similar conditions. This was not supported by the objective data analysis, however, which found no significant difference in the number of microphone keyings or total time on frequency between the Baseline / FDMS scenario pairs.

Nearly all controllers felt that the flight crew announcements when starting FDMS and on check-in were necessary. On average, controllers agreed that "company spacing" is an acceptable phrase for flight crews to use when announcing FDMS. They also agreed that it was acceptable for FDMS aircraft to not announce every speed change. On average, controllers agreed that flight crews announcing FDMS termination by saying "terminating company spacing" was acceptable. On average, controllers strongly disagreed that it is necessary for the flight crew to provide the FDMS spacing interval.

When asked specifically about flight crew use of third party traffic call sign in FDMS communications, three controllers found it "necessary", three others found it "desirable", and two found it "undesirable". The two that found it undesirable also reported that it was unacceptable and resulted in "too much talking." However, none felt that the addition of call sign made communications difficult, and nearly all controllers (including the two that reported call sign use undesirable) agreed that flight crew use of traffic call sign in FDMS communications might be necessary during merging operations. On average, controllers somewhat agreed that flight crew use of traffic call sign in FDMS communications made it easier to detect problems.

D. Human Performance

1) Workload: The workload results are based on the responses to the Bedford Workload Rating Scale (Figure 6) [25]. In the post-simulation questionnaire, controllers reported that the overall average workload for FDMS was "easy / workload low". All controllers agreed that their workload was acceptable, and felt that FDMS reduces workload, as compared

to controlling a similar number of aircraft under similar conditions. All but one of the controllers rated FDMS as "no more difficult than current operations". The dissenter noted that FDMS was "more difficult than most current operations, but the average controller can do it".
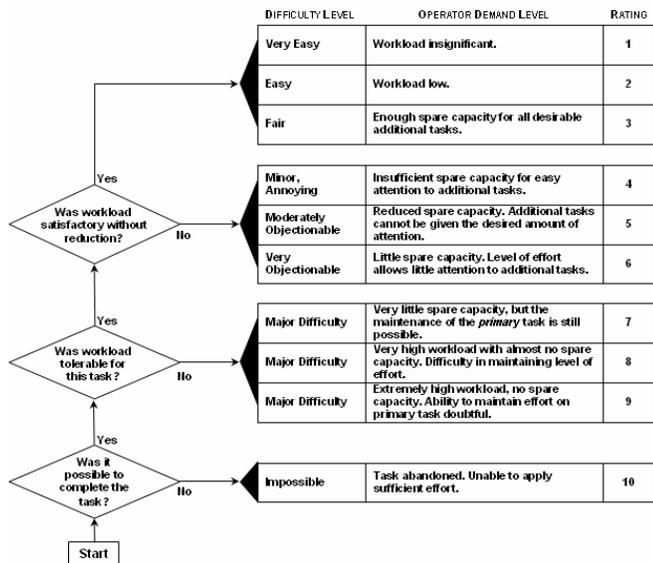
Figure 6. Bedford Workload Rating Scale

For the Baseline/FDMS scenario pairs, the results do not show that FDMS reduced controller workload over baseline operations. In the FDMS disruption case, controllers reported experiencing a higher level of workload as compared to the baseline. This suggests that significant FDMS disruptions such as an aircraft following the wrong TTF, can increase a controller's workload over baseline levels. For the other cases tested, FDMS did not appear to increase workload.

2) Situation Awareness: All controllers agreed or completely agreed that their level of traffic awareness during FDMS was acceptable, that they were able to project FDMS aircraft locations into the future, and that they were able to predict losses of separation during FDMS.

V. CONCLUSIONS

This paper focuses on FDMS and presents the subjective and objective results of a human-in-the-loop simulation that examined the concept from the en route controller perspective during an in-trail operation, from aircraft top-of-descent through entry into terminal airspace in a Continuous Descent Arrival (CDA). Termed FDMS 4, the simulation was conducted in May and June of 2007 and is part of a development and maturation process that is underway for FDMS. The impact of FDMS on controller operations during entry to a CDA, as well as human performance, operational impact, and communications issues were examined. Concept acceptability and the handling of non-normal situations were also evaluated.

Controllers reported on average that FDMS during en route descent operations was acceptable, desirable, and an improvement in operational efficiency. FDMS allowed for acceptable workload and traffic awareness – even in the event of spacing disruptions. Controllers had no issues intervening with FDMS traffic when necessary; however, controller responses were varied on whether it was acceptable to give FDMS aircraft priority. FDMS helped reduce overall controller interventions in an arrival stream under normal conditions, but did not increase or decrease total interventions for overall sector traffic sets under normal conditions or when spacing disruptions were introduced.

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DISCLAIMER

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