BENEFITS OF CONTROLLER-PILOT DATA LINK ATC COMMUNICATIONS IN TERMINAL AIRSPACE

FINAL REPORT

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16. Abstract

This report documents a Federal Aviation Administration (FAA) study that was conducted to demonstrate and quantify benefits associated with the implementation of controller-pilot Data Link communications in terminal airspace. The study was supported by the FAA Data Link Program office. The manned simulation research was performed at the William J. Hughes FAA Technical Center by the Data Link Branch (ACT-350).

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FAA Data Link Program

Ms. Karen Burcham was the Data Link Program Manager with overall responsibility for Terminal Data Link and Benefits Assessment Projects.

Ms. Barbara Cassada, ATCS, was the Data Link Branch Manager responsible for the overall management and development of Data Link services.

Mr. Evan Darby, Jr., ATCS, was the Test Director for the FAA Technical Center, and provided resource and logistics management; simulation, test plan, scenario development/debugging, voice/data reduction; and air traffic control and Data Link expertise.

Mr. Timothy Hancock, ATCS, was the Test Director for FAA Headquarters, and provided controller training; NAS user liaison and data acquisition; simulation, test plan, and scenario development; and air traffic control and Data Link expertise.

Mr. Nicholas Talotta was the Ground Data Link Technical Program Manager, and provided engineering, system and test plan development.

Mr. Eric Reumann, ATCS , provided New York TRACON expertise, and simulation and test plan development.

Mr. James Cherrey, ATCS, provided voice systems analysis and air traffic control expertise; simulation debugging, scenario development, and ETG pilot training.

Mr. George Chandler provided test bed engineering and software in the development of Data Link services.

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Mr. John Van Dongen provided test bed engineering and ARTS IIIE/Data Link software development.

Mr. Paul Dawson provided automation support for scenario development and data analyses.

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Dr. Clark Shingledecker, NTI, Inc., provided research design and analysis, test plan development, as well as human factors support. He prepared the most significant portion of this report.

Mr. Craig Morris, Advanced Management Technologies, Inc., was Senior Data Link Engineer, and Chairman of the Data Link Benefits Study Team.

Mr. Joseph Lunder, ATCS, ret., TMA, Inc., provided ARTS IIIE automation support, test plan development, air traffic control, and Data Link expertise.

Mr. Tom Stiney, Programmer, TMA, Inc. provided automation support for scenario development and data analyses .

Ms. Virginia Stouffer, MCA Research Corporation, Senior Operations Research Engineer, provided system performance measurements, economic benefits analysis, and test plan development.

Mr. Tushar Amin, MCA Research Corporation, Operations Research Analyst, provided system performance measurements, economic benefits analysis, and test plan development.

Mr. William Fischer, Boeing Corporation, Flight Deck Engineer, Data Link Crew Operations, was Test Director for Boeing Corporation, and provided flight simulator Data Link system integration and expertise.

Ms. Jean Crane, Boeing Corporation, Flight Deck Engineer, Data Link Crew Operations, was Test Director for Boeing Corporation, and provided flight simulator Data Link system integration and expertise.

Mr. Raymond J. Sanford, Airline Pilots Association, Continental Airlines, Line Check Airman, provided airborne expertise and test plan development.

<u>New York Terminal Radar Approach Control, Newark Sector, Personnel</u>

Air Traffic Control Specialists:

Mr. Steve Adamek III	Mr. Tom Fitzgerald	Mr. Dave Harvey
Mr. Tim Byrnes	Mr. Donald Freedenberg	Mr. Michael Pitt
Mr. Frank Caputo	Mr. Gary Graswald	Mr. John Samacicia

Supervisory Air Traffic Control Specialists:

Mr. Mike Dietrich	Mr. Robert Marsh	Mr. Ken Vernam

Airspace and Procedures Specialist:

Ms. Patti Moss

<u>Air Traffic Data Link Validation Team Support:</u>

Mr. James Cherrey	ATCS, Miami ARTCC
Mr. Joseph D'Alessio	ATCS, Southern California TRACON
Mr. Edward Brestle	Crown Comm. Inc. (ATCS, ret.)

<u>The Data Link Benefits Study Team:</u>

Mr. Tushar Amin	Mr. Timothy Hancock	Mr. Raymond Sanford
Mr. Gregg Anderson	Dr. Clark Shingledecker	Mr. Joseph Lunder
Mr. Evan Darby, Jr.	Mr. Craig Morris	Ms. Virginia Stouffer
Mr. Nick Talotta	Mr. Eric Reumann	

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EXECUTIVE SUMMARY

This report documents the results of the second Federal Aviation Administration (FAA) manned simulation study designed to identify and quantify some of the benefits of Controller-Pilot Data Link Communications (CPDLC). The study specifically focused on CPDLC in the terminal air traffic control (ATC) environment, and addressed potential economic benefits to National Airspace System (NAS) users, productivity and safety benefits to the ATC system, and performance and workload benefits to air traffic controllers. Air traffic controllers, ATC supervisors and pilots participated in high fidelity simulation tests in which a combined voice radio and Data Link communication system was used to control traffic in terminal airspace.

The study demonstrated that controllers using CPDLC were able to provide ATC services that improved terminal approach control productivity and increased flight efficiency in congested arrival airspace. These effects were reflected in reduced arrival delays and more effective use of airspace when compared to an environment where only voice radio communications were available. In addition, the results of the study indicate that these improvements were accompanied by an increase in the margin of safety, and a reduction in controller workload and stress. Economic cost savings associated with the findings were computed to estimate the potential magnitude of CPDLC effects and their significance to NAS users.

<u>APPROACH</u>.

The study examined operational ATC performance at control positions within the Newark area of the New York Terminal Radar Approach Control (TRACON). The first and second experiments tested the ability of CPDLC to reduce delays and improve traffic flow at the Newark area jet arrival feeder and final positions. The third experiment evaluated CPDLC at a satellite airport arrival position.

All three experiments were conducted using a case study methodology. Test scenarios were built to duplicate air traffic data sample periods taken from the Newark area. In experiment 1, data obtained from the operational baseline period were compared to data collected under high fidelity simulation conditions using a combined voice and Data Link communications system. In experiments 2 and 3, the size of the baseline traffic sample was increased to assess impact of Data Link on performance when ATC demands were greater than those presented on operational baseline days. In these experiments, testing was conducted using voice-only communications as well as CPDLC, plus voice, in order to provide comparable baseline data.

A group of three controllers and one supervisor from the Newark area participated in each of the three 1-week test sessions. Each test session constituted a full replication of the three experiments. Thus, all of the nine controllers and three supervisors participated in all three experiments.

KEY RESULTS.

Experiment 1 provided a direct comparison of actual operational performance in the Newark area jet arrival airspace under current voice-only communications to test performance with both Data Link and voice radio communications available. The Data Link test scenario presented a temporal and spatial pattern of flights that was identical to that experienced by controllers on the historical baseline day. The primary Data Link benefit hypothesized for this experiment was an ability to postpone or eliminate the air traffic holding outside the Newark area that had occurred on the baseline day because of traffic volume.

The results of the experiment showed that, when Data Link communications were available during testing, the Newark area controllers were able to avoid the use of holding that had occurred on the operational baseline day. This resulted in the average flight arriving at the airspace boundary 1.98 minutes sooner than it had on the historical baseline day. In addition, mean flight distances and times within the terminal airspace were reduced by an average of 6 miles and 3 minutes, and earlier mean arrival times at EWR (Newark) were achieved with Data Link. The productivity of the sector also was improved as the average number of flights handled by the controllers during the test period increased by two and the average number of aircraft landed increased by four with Data Link.

Beyond these NAS user and system benefits, controller workload during Data Link testing was either reduced or remained at a level equivalent to that normally experienced in the Newark area jet arrival positions during a traffic rush period. Operational assessments likewise suggested that the margin of safety under Data Link testing was higher than normal for the airspace under similar traffic demands in the operational airspace.

Experiment 2 assessed the impact of Data Link when additional traffic was added to the Newark area jet arrival flow. As in experiment 1, the test scenario was derived from an historical baseline period. Since only normal restrictions had been placed on arriving flights during the baseline period, 10 aircraft were added to the original 55 flight scenario to increase the demand on ATC resources. The additional aircraft consisted of actual flights that were scheduled to arrive during the selected rush period, but had been delayed for various reasons. The primary benefit hypothesized for this experiment was an improved ability to maintain arrival traffic flow during Data Link test runs when these were compared with equivalent test runs conducted under voice-only communications.

The results showed that, with Data Link, the Newark area controllers were able to reduce sector entry delays by an average of 1.36 minutes, and reduce flight times within the airspace by .7 minutes and distances by 1.7 miles. An average of 2.75 more flights also were landed during the test period with Data Link than when only voice communications were available. Holding and restrictions were required to handle the increased volume in both voice-only and Data Link runs. However, these measures were used less frequently and for shorter periods with Data Link. The resulting improvements with Data Link were somewhat smaller than those observed in experiment 1, but they were achieved under traffic demands which were 35 percent greater.

Operational assessments indicated that the margin of safety under Data Link testing was higher than normal for the airspace under similar traffic demands. Under voice-only testing, none of the runs were rated as having an improved margin of safety. Finally, quantified assessments showed that controller workload was significantly lower for both the feeder and final controllers when using Data Link and voice than when using voice radio alone.

Experiment 3 examined Data Link's impact on the Newark area satellite arrival position (MUGZY). This airspace requires controllers to handle commuter arrivals to Newark, arrivals to Teterboro, and arrivals to several other satellite general aviation airports. The airspace is complex because of crossing traffic with a variety of aircraft types and multiple destinations. However, the traffic volume in the test scenario was not as high as that experienced in the Newark area jet arrival. The experiment was conducted to determine whether the addition of Data Link communications would improve service to both commuter and business/general aviation arrivals.

Unlike experiments 1 and 2, this experiment failed to yield evidence for significant benefits of CPDLC. While small improvements in sector performance were obtained in some test runs, others showed no significant changes. The absence of significant Data Link benefits in this experiment was attributed to differences in the ATC problems presented by the Newark area satellite arrival position and the jet arrival positions. Performance in the Newark area jet arrival airspace was strongly affected by high traffic volume and associated limitations in the capacity of the communications channel. Conversely, communications requirements at the Newark area satellite arrival position were much lower, and performance appeared to be primarily limited by traffic complexity and high coordination requirements.

A pilot sub-study was performed in conjunction with this benefits study in two flight simulators at the Boeing Airplane Systems Laboratory in Seattle, WA. This sub-study produced results which directly addressed requirements for the pilot Data Link interface during terminal operations and for effective flight deck and controller-pilot Data Link procedures. The detailed findings of the sub-study are presented in appendix C of this report.

CONCLUSIONS.

The overall conclusion that can be drawn from this study is that CPDLC will provide significant benefits when implemented in terminal ATC environments. As a minimum, all terminal areas will benefit from reduced controller workload and task related stress, as well as an increase in the margin of safety as communications errors and losses are prevented. In those terminal environments similar to the jet arrival airspace tested in this study, where ATC performance is limited by the restricted nature of the voice radio system, CPDLC will expand the communications channel. The direct effects of this expansion will be to permit simultaneous communication with multiple aircraft, the relegation of repetitive, time-consuming messages to Data Link, and the reduction of radio frequency congestion, making the radio more available for time-critical clearances. In such situations, CPDLC will eliminate the artificial restriction on controller performance, and (as shown in experiments 1 and 2) make reduced flight delays and improved use of airspace possible. In addition, CPDLC will permit sharing of communications tasks and allow more productive use of handoff controllers that are assigned to busy terminal sectors.

BENEFIT ESTIMATION AND AGGREGATION.

The final task of this study was to translate system performance improvements observed in the experiments to estimates of some of the economic benefits that would be associated with the implementation of terminal CPDLC. Economic benefits that would accrue to NAS users were evaluated using a modeling technique which assessed the system-wide impact of installing CPDLC at 58 of the busiest national airports. The average minimum hourly arrival rate improvement of 9.6 percent derived from the experimental results was applied to the NAS and annualized. The findings of the modeling exercise showed that airborne and ground operational delays would be reduced by 6.1 percent resulting in a reduction in annual operational costs to NAS users of more than $152 million.

In evaluating the significance of these findings, it should be noted that the analysis addressed only one dimension of CPDLC's potential benefit. The estimated cost savings to NAS users are restricted to those produced by implementing Data Link for arrivals in the terminal environment. They do not include terminal benefits at departure positions, benefits that are associated with en route or tower CPDLC, or the positive effects on safety and controller workload that were demonstrated during this study.

Such additional benefits must be considered when assessing the total impact of Data Link implementation. For example, the results of the experiments performed for this study indicate that CPDLC will supply direct benefits to the FAA in the form of reductions in the required costs of operating the NAS and of upgrading its capabilities.

An immediate FAA economic benefit of CPDLC's ability to enhance the margin of safety will be a reduction in the resources that must be devoted to investigation and analysis of operational errors and deviations induced by communications problems. The expanded communications channel created by implementing CPDLC will also have the potential to significantly reduce the rate of growth in requirements for additional radio frequencies, and make it possible to postpone requirements for implementing a Next Generation Communications (NEXCOM) system. Finally, the increased controller productivity and reduction in controller stress created by CPDLC can be expected to lower the rate at which staffing levels are raised to meet increasing traffic demands, provide more consistent controller performance, and increase career longevity.

1. INTRODUCTION.

1.1 PURPOSE.

This report documents the results of a study designed to assess the impact of controller-pilot Data Link air traffic control (ATC) communications. The study employed real-time, controller and pilot in-the-loop simulation to provide an empirical basis for quantifying some of the benefits of implementing Data Link ATC communications in terminal airspace. For the purposes of this study, potential Data Link benefits were broadly defined to include reductions in operating costs for aircraft operators and improved service to their customers, enhancements to ATC system productivity and safety, and increases in the performance capabilities of air traffic controllers.

The study was planned and executed by the Data Link Benefits Study Team. This group of government and industry representatives was convened by the Federal Aviation Administration (FAA) in January 1994, to develop approaches for measuring and demonstrating the impact of implementing Data Link in the domestic ATC environment. The study described here was the second in a series of tests and analyses aimed at accomplishing this goal.

1.2 BACKGROUND.

1.2.1 Data Link Implementation Plans.

Over the past several years, the FAA has evolved a comprehensive plan for building an air traffic management (ATM) system. This system will support future global flight planning, aircraft operation, and ATC services through the introduction of advanced communications, navigation, and surveillance technologies. A key feature of the future ATM will be the use of digital Data Link communications as a primary means for exchanging aeronautical information and delivering ATC services.

Preliminary applications of Data Link have included predeparture clearance (PDC), digital Automatic Terminal Information Service (ATIS), selected Flight Information Services (FIS) and oceanic ATC services. The next step in the FAA plan currently calls for the implementation of domestic, in-flight Data Link ATC services to begin in 1998-1999 with the introduction of direct controller-pilot communications in the en route and terminal ATC environments. At this initial stage, controllers will have the capability to uplink a variety of clearance and advisory messages to equipped aircraft, and aircrew will be able to downlink reports and ATC requests. These services have been referred to alternatively as Two-Way

Data Link (TWDL) or Controller-Pilot Data Link Communications (CPDLC)[1]. Performance standards and a message dictionary for such Data Link communications have been published by the RTCA (1993).

Early in the next century, Data Link implementation will begin to expand to a broad range of automated information exchanges. These end-state applications will provide a connection between airborne and ground-based data and computing resources that will optimize approach traffic flow, enable the routine use of 4-D navigation and permit long range conflict detection and resolution.

1.2.2 Justification for Implementing CPDLC.

Execution of the plan outlined above will require extensive cooperation between government and private industry, and major resource expenditures by both parties. The FAA will be responsible for implementation of the integrated telecommunications network needed to support Data Link and development of associated ATC software and hardware. Likewise, users of the National Airspace System (NAS) must elect to equip a significant number of aircraft with the avionics and aircrew interfaces needed for Data Link communications.

Growing competition for limited federal budget resources and high aircraft and air carrier operating costs demand that these government and private investments be supported by substantial evidence that the introduction of Data Link ATC services will result in significant benefits to NAS users and to the domestic ATC system. There appears to be general agreement within private industry and the government that major benefits will be achieved when Data Link is used to enable advanced automation. However, because of limited evidence for benefits associated with basic CPDLC, the case for developing the required system and equipping aircraft for this initial stage of domestic implementation has not yet been fully justified.

In response to these concerns, the FAA has initiated a program of real-time simulation research and analysis to identify and quantify benefits that will accompany the implementation of a CPDLC system. The first study conducted under the program addressed Data Link benefits in the en route ATC environment (Data Link Benefits Study Team, 1995). This report documents the results of a second study designed to assess Data Link benefits in terminal airspace.

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[1]Unless otherwise noted, the terms “Data Link” and “CPDLC” are used interchangeably in this document.

1.3 PRECURSORS OF DATA LINK BENEFITS.

Any benefits that may be associated with CPDLC will be realized indirectly through changes in ATC capabilities and performance that are made possible by digital communications technology. For this reason, the process of defining studies to assess benefits began by examining some problems which currently exist in ATC communications, and the direct effects that the introduction of Data Link can be expected to have on them.

1.3.1 Frequency Congestion.

One of the primary factors that has driven the development of Data Link has been the growing utilization of voice radio in the NAS. Because the voice channel is available to only one speaker at a time, increasing traffic volume rapidly leads to frequency congestion. When the channel becomes saturated, system performance suffers as clearances become less timely and the exchange of information is reduced to an absolute minimum.

In order to understand how Data Link is likely to affect system capabilities, it is important to examine the way in which controller performance is affected by frequency congestion. When debriefing controllers about the factors which influence workload experienced on the job, it is common to hear that "it's not the number of aircraft in my airspace that creates workload, but what I have to do with them and how much time I have to do it."

Such statements emphasize a close relationship between workload and the amount of communication required to maintain control over air traffic. They also suggest that any factor which limits the amount of time available to perform required communications with aircraft will increase controller workload or reduce the efficiency with which ATC tasks can be accomplished. As frequency usage is increased, high workload is precipitated by a proportional limitation in the time available to carry out required communications, rather than an inherent inability of the controller to handle the air traffic or by saturation of the airspace itself.

From a theoretical point of view, this workload problem can be seen as a special combination of the data limitations and resource limitations on human performance discussed by Norman and Bobrow (1975). In the case of frequency congestion, constraints imposed by the simplex nature of the radio system produce a data limitation on controller performance by preventing timely communications. That is, performance is limited by the physical constraints of the system rather than the information processing resources of the controller. However, as a result of the shrinking performance windows, mental resource limitations come into play and workload increases as controllers attempt to maintain system performance by reverting to tactical control strategies which tax their perceptual, cognitive, and speech-motor capacities.

Because of the close coupling between the controller's ability to make effective use of available system capacity and voice frequency usage, a fundamental measurement taken during high fidelity Data Link simulations at the FAA Technical Center has been the extent to which Data Link reduces use of the radio channel to communicate with aircraft. In each of these studies, subject controllers were asked to control simulated air traffic using traditional voice communications alone, and under conditions where both voice and Data Link channels are available. During Data Link trials, the controllers were instructed to perform the ATC task as safely and efficiently as possible, and to use the two available communications systems in a manner which they felt was most effective for accomplishing their objectives.

Data Link's effect on voice radio frequency usage has been measured in both en route and terminal simulation studies. In an en route operational evaluation, the provision of an initial service capability (transfer of communication and altitude assignment) reduced the number of voice transmissions initiated by controllers up to 41 percent. It also reduced the total amount of time that the controllers occupied the radio frequencies up to 45 percent (Talotta, et. al., 1990). Furthermore, as the proportion of aircraft in the test scenarios equipped with Data Link was raised from 20 percent to 80 percent, the overall efficiency of ATC communications improved as requirements for repetitions of voice messages and clarification of misunderstood clearances decreased.

Similar dramatic reductions in voice radio usage were obtained in terminal testing under 75 percent aircraft Data Link equipage. In this situation, where controllers could transmit speeds, headings, and initial contact responses, as well as the services used in the en route study, the number of voice messages issued by controllers dropped by 50 percent over the voice-only test conditions, and radio channel occupation time by controllers fell by 60 percent (Data Link Development Team, 1991). In other studies, a full complement of Data Link ATC services have produced even greater reductions in radio usage with high aircraft equipage levels (e.g., Air Traffic Data Link Validation Team, 1994).

1.3.2 Communications Errors.

In addition to its potential for reducing communications-induced limitations in effective system capacity, analyses performed at the FAA Technical Center also have indicated that Data Link has the ability to reduce the occurrence of common ATC communications errors that degrade efficiency and can affect flight safety.

Incidence estimates available from a number of sources clearly show that communications problems are a major source of concern in the present ATC system. In 1988, the FAA noted that 23 percent of all operational errors (aircraft minimum separation violations) were caused either directly or indirectly by communications mistakes. Similarly, compilations of reports provided on a voluntary basis by aircrew and controllers to the Aviation Safety Reporting System (ASRS) have indicated that 70 percent to 80 percent of all potentially hazardous incidents that are reported implicate ineffective verbal information transfer; and that a clear majority of these involve air-ground radio communications (Billings and Reynard, 1981; FAA, 1988). Common categories of human error which appear to be the primary sources of the cited communications problems include acoustic confusion and transposition of alphanumerics, pilot readback error, controller "hearback" error, misinterpretation caused by poor pronunciation and failure to use standard phraseology, and improper radio keying technique.

Several general human performance limitations appear to combine with the features of a simplex voice radio system to promote the errors that are commonly observed in the ATC environment. These traits include: (1) the limited rate at which humans can produce and comprehend the speech signal (partially defining the point at which radio frequency congestion becomes problematic), (2) short-term memory limits for the content of the transient acoustic displays used in radio communications, (3) the tendency to rely on expectation in the absence of unambiguous data, (4) human susceptibility to phonetic confusion in acoustic displays, (5) the relative unreliability of the human as a monitoring device in a multiple task environment, and (6) the tendency for humans in a high workload situation to adapt by shedding load, often sacrificing highly redundant, prescribed radio communications formats (Shingledecker and Talotta, 1993).

Unlike voice radio, Data Link offers a communications medium which transmits coded, digital data to individual addressees. This feature of Data Link can be expected to alleviate the problems induced by the human-system interaction at nearly all stages of the communications process. While Data Link cannot compensate for poor controller decisions, the message formulation stage should be improved by providing reasonableness and logic checks of the digital data. Message composition can be assisted by storing common messages for selection from a menu, and by employing automatic checks on controller input formats to prevent the transmission of ambiguous clearances. Furthermore, message composition would not be impeded by the delays experienced when the radio channel is in use by pilots.

Message transmission also will be improved because Data Link will assume some portion of the load on congested radio frequencies. As discussed in section 1.3.1, this will not only increase the availability of the voice frequency, but also reduce controller workload and increase the timeliness of clearance delivery by permitting controllers to communicate when necessary -- not merely when the channel is available. In addition, those messages carried by Data Link will be effectively immune to degradation by noise and blocking that plague an analogue radio system and impair pilot perception. “Stolen clearances” and message (call sign) detection by the pilot will be totally eliminated as a source of error since this task will be assumed by Data Link's discrete addressing system. Likewise, message interpretation will be enhanced because pilots and controllers will have a persistent, storable reference of message content, and because available evidence suggests that a visual display may be less prone to misinterpretation than an acoustic display.

Finally, the acknowledgment and verification stage of the communications process, which is a human responsibility in the voice radio system, will be largely allocated to Data Link. However, rather than being assumed by Data Link in an analogous sense, the verification process will be built into each transmission as the system automatically verifies the integrity of message content reaching the receiver, assures the originator that the response is from the intended receiver, and monitors for transaction failures.

Based on the analysis summarized above, Shingledecker and Talotta (1993) attempted to estimate the extent to which the introduction of Data Link will ameliorate communications errors. Using ASRS data including 2700 reports of communications problems, their findings indicate that Data Link would produce a major reduction in communications problems that form 45 percent of all reported communications incidents. These include ambiguous, incomplete, and garbled messages, failures to detect clearances, phonetic confusions, and transposition errors. A further 54 percent of incidents would be at least partially reduced by Data Link. These incidents include untimely issuance of clearances caused by congested or blocked frequencies and those cases where aircraft perform uncleared maneuvers because of confusions about the intended receiver of a message or because of misinterpretation of the clearance itself. Only 1 percent of all problems would be unaffected, these being situations where the controller issues a logically reasonable, but erroneous clearance because of faulty decision making.

1.4 EN ROUTE BENEFITS STUDY.

The data and analyses discussed above suggest that the introduction of CPDLC will significantly improve both the quality and the capacity of the communications channel between controllers and aircrew. The first research effort aimed at demonstrating that these direct effects of Data Link could be reflected in quantifiable benefits to the NAS and its users was conducted in 1994 (Data Link Benefits Study Team, 1995). The two experiments of the study focused specifically on operational en route airspace where frequency congestion had been cited as a factor in producing deficient aircraft operation and sector productivity during traffic rush periods.

Appendix A presents an overview of the research approach that was used in the en route benefits study, as well as a summary of the key findings. Briefly, the results showed that controllers using Data Link were able to provide ATC services that improved en route sector productivity and efficiency. These effects were reflected in reduced arrival and departure delay, flight time, and flight distance in comparison to a current operational environment using only voice radio communications. In all cases, the results were achieved with a margin of safety which met, or exceeded, current ATC standards, and with no indication of excessive controller workload.

1.5 DATA LINK FOR THE TERMINAL ENVIRONMENT.

The en route study described in appendix A produced empirical support for the hypothesis that implementing the ground infrastructure for Data Link and equipping aircraft to participate in CPDLC will return significant benefits to the NAS and its users. However, because incremental costs will be incurred to implement the system in different ATC environments, a separate case must be made to justify the application of Data Link in terminal airspace.

A priori support for terminal implementation of CPDLC can be derived from the argument that Data Link should be a “seamless” system. That is, as in the existing voice radio system, similar communications procedures should be used as aircraft transition through oceanic, en route, terminal and tower ATC environments. From a human factors standpoint, such compatibility promotes accurate communication and avoids unnecessary complication of aircrew tasks. Assuming the validity of this position, terminal Data Link is at least partially justified by any benefits that may be gained through en route implementation.

Beyond the indirect argument for a seamless communications system, the fundamental nature of operations in congested terminal airspace suggests that Data Link may provide independent benefits in this environment. Busy terminal areas are clearly the most significant bottlenecks within the ATC system. This is especially the case under the airline “hub and spoke” concept of operations where airport arrivals and departures often form large, overlapping traffic clusters during two or more daily rush periods.

When traffic congestion exceeds the capacity of the terminal area, arriving aircraft may be denied access to the terminal airspace. Such effects can rapidly spread throughout the massively interconnected ATC system causing aircraft operating inefficiencies in distant en route airspace and wide-spread ground delays at remote airports. Airline operations are further affected as departures are delayed, late arriving passengers miss connecting flights, and flights are canceled or must depart with large numbers of empty seats.

Terminal capacity is ultimately determined by the physical capacities of airport runways, taxiways, and gates, and by variable factors such as weather. However, within these boundary conditions, the *effective* capacity of the airspace can be restricted by other factors. One of these is the limited channel capacity of the ATC communications system.

Heavy traffic demands often can create a situation in which a terminal controller becomes engaged in prolonged periods of continuous verbal communication to send all of the clearances needed to guide the pilots of arriving, departing, and transient aircraft. In addition, the requirement to convey lengthy advisory messages to aircraft entering the terminal area rapidly expends the limited communication time available to tactically control closely spaced aircraft on approach and departure flight paths. The problem can be further exacerbated by misunderstandings and readback errors which require correction and further congestion of the frequency. Thus, as noted in section 1.3 of this report, the limitations imposed upon the controller by the simplex voice radio system can affect the timeliness of clearance delivery and impair terminal ATC effectiveness. The result is a reduction in the *effective capacity* of the system which can cause flight delays as costly as those produced by insufficient airspace or runway capacity.

As shown by the results of the en route benefits study, the introduction of Data Link to frequency-saturated airspace can expand the communication channel and prevent or reduce aircraft delays. However, differences between the terminal and en route ATC environments could affect the ability of Data Link to ameliorate such problems in terminal airspace. Terminal ATC and flight deck operations generally are more tactical and time-compressed than en route operations. Control clearances often must be carefully timed to achieve effective results and aircrew are heavily involved in many essential cockpit tasks during the approach and departure flight phases. In such situations, it is possible that any potential Data Link benefits could be outweighed by the effects of inherent transmission delays, crew task interference, or loss of the crew situation awareness that is provided by the broadcast voice radio channel. Terminal airspaces also are smaller and experience higher traffic densities than typical en route sectors. Consequently, controllers may not have as much freedom to exercise all of the control options that might be afforded by Data Link communications.

2. STUDY OBJECTIVES.

The primary objectives of this study were to determine whether controller-pilot Data Link ATC communications can yield significant benefits in terminal airspace, and to measure some of these benefits if they were shown to exist. Specifically, the study employed real-time, high fidelity simulation to assess the extent to which the increased communications capacity and accuracy provided by Data Link can improve the effectiveness of ATC operations in congested terminal airspace. Measurements evaluated potential changes in flight delays and aircraft operating costs, as well as effects on the workload capacity and productivity of terminal controllers, and the overall efficiency of the ATC system that may be associated with the introduction of CPDLC. These assessments also included measures of relative system safety.

A final objective of this study was to use the local benefits obtained from the empirical results of the experiment to project system-wide benefits that would result from improved terminal efficiency. This objective was addressed through the application of airspace and air traffic modeling techniques.

3. SUMMARY OF APPROACH.

The experiments described in the succeeding sections of this paper used a case study methodology. Rather than synthesizing scenarios based on a general model of a congested terminal ATC environment, the study addressed an archetypal example of highly saturated terminal airspace within the NAS. Test scenarios were built to duplicate air traffic on sample days taken from the Newark Area of the New York Terminal Radar Approach Control (TRACON). Data obtained under current voice radio communications were compared to data collected under high fidelity simulation conditions using a combined voice and Data Link communications system. Additional testing examined the impact of Data

Link on performance with greater levels of air traffic than those presented on operational baseline days. In these scenarios, data using voice-only communications were collected to provide baseline comparisons.

The results of the study were nationalized by measuring improvements in en route airspace and at destination airports that are affected by delays attributable to the Newark area. In addition, efforts were made to extend any observed improvements in the Newark terminal area to other busy TRACONs and their respective surrounding en route airspaces.

4. TEST CONDUCT.

4.1 PROBLEM DESCRIPTIONS AND DATA LINK HYPOTHESES.

The ATC problems that were addressed in this study were based on current operations in the New York TRACON. The TRACON is divided into five independent areas. The experiments focused on the Newark area which contains eight radar positions.

The primary task of the Newark area is to control arrivals and departures for Newark International Airport (EWR). Operations at Teterboro (TEB), a major general aviation airport serving private business aircraft in the New York metropolitan area, represent a second key source of air traffic demand. Finally, the area controls arrivals and departures for 13 additional satellite airports within its boundaries, and overflights departing from, and destined for, airports served by other areas in the New York TRACON.

High traffic volume and other factors at the EWR make the Newark area one of the most problematic terminal airspaces within the NAS. Data collected during the first 10 months of 1995 show that the number of ATC operations conducted at EWR was relatively modest in comparison to some other major metropolitan airports (FAA, 1995). For example, Chicago's O'Hare International Airport (ORD) had the highest level of activity for the period, completing more than twice the number of ATC operations as EWR. In addition, ORD was attributed with 50 percent more flight delays in excess of 15 minutes than EWR.

However, other data suggest that EWR experiences a disproportionately high number of traffic problems. The absolute number of flight delays attributed to traffic volume were 57 percent higher at EWR than ORD. Furthermore, when the two airports are compared on a relative basis, EWR had 10 percent more total delays per operation than ORD, 250 percent more volume delays per operation, and 33 percent more delays of arriving flights per operation.

4.1.1 Newark Area Jet Arrivals.

Jet arrivals at EWR are processed in a feeder/final configuration. Figure 1 presents a simplified map of the Newark area feeder and final positions along with a depiction of the typical arrival traffic flow patterns within the airspace. Under the southwest flow, aircraft are passed from the WARRD/PENNS feeder position to the SHAFF final vector position and aircraft land on Runway 22L. In the northeast flow, the aircraft are passed from the SHAFF/PENNS feeder position to the WARRD final vector position for landing on Runway 04R. In both traffic flows, Runway 11 normally accepts the majority of turboprop arrivals.

The feeder position in both traffic flow configurations must blend from three to six streams of traffic and provide initial in-trail spacing to the final position. The feeder is also required to handle overflights from adjacent approach controls and other areas in the New York TRACON, as well as some low altitude departures. When Runway 11 is not available, the feeder also must sequence all turboprop arrivals into the flow of jets for the primary runway.

The feeder and final positions work four major arrival traffic pushes each day. During any one of these, traffic volume can be great enough to exceed airspace and/or airport capacity. As volumes begin to increase, the arrival controllers employ speed control and vectors to contain arrivals within their airspace. When the airspace eventually becomes saturated, holding is instituted at the outer fixes. Decisions regarding the arrival fixes at which traffic will be held are based on Traffic Management and supervisory inputs. The probability that holding will be instituted during a given traffic rush period is dependent upon a number of variables including the arrival times of individual flights, the effectiveness of anticipatory Traffic Management initiatives, and weather. Because Newark is a major airline hub airport, traffic holding is responsible for departure ground delays at airports across the nation and in-flight delays in wide areas of en route airspace.

The problems experienced in the Newark area are a result of many interacting factors. These include airspace limitations, complex interactions with other New York metropolitan area airports, satellite airport traffic, and noise abatement restrictions. Within these constraints however, the high traffic volumes within the Newark area also produce radio frequency congestion. For example, during a rush period with Runway 11 unavailable, the feeder position can be faced with as many as six initial contact calls from aircraft at the arrival fixes while attempting to provide efficient sequencing for flights already within the airspace. Such

Feeder/Final Sectors

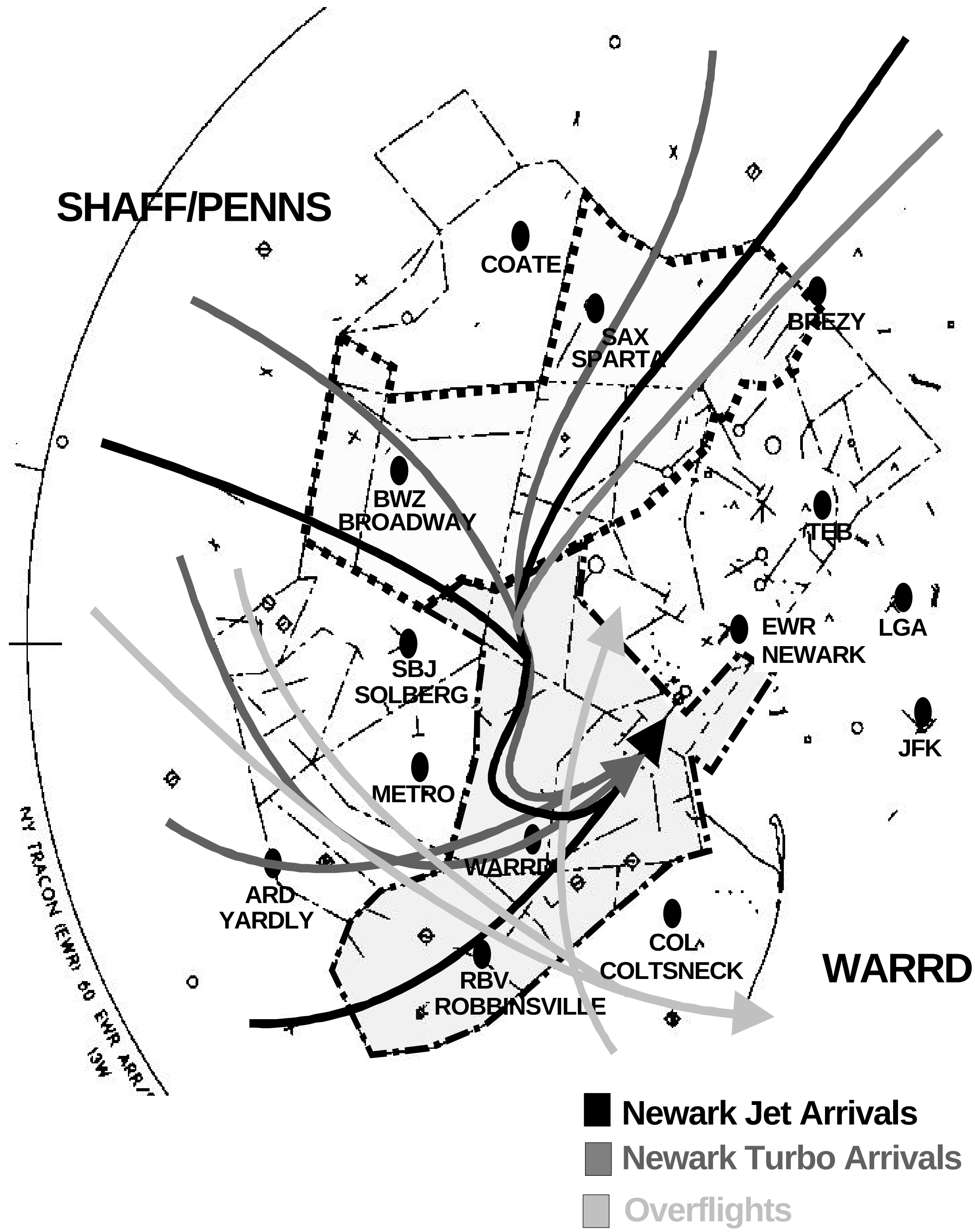

FIGURE 1. NEWARK AREA JET ARRIVAL AIRSPACE

situations can limit ATC performance by preventing timely tactical communications and promoting communications errors.

The hypothesis that was tested in experiments 1 and 2 of this study was that the addition of Data Link to the Newark area jet arrival positions would improve communications capacity and accuracy, thereby enhancing controller performance, ATC productivity, and flight efficiency. The primary predicted effect of this improvement on controller procedures was a shift of nontime-critical messages to Data Link. These were expected to included transfer of communication messages, initial contact calls from aircraft entering the airspace, and initial control clearances. The resulting reduction in frequency congestion was predicted to make the voice channel more available for issuing required tactical control clearances in a timely manner.

The indirect benefits that were hypothesized to be associated with these improvements were:

a. Postponement or elimination of the requirement to employ inefficient control strategies and holding due to airspace saturation.
b. Decreased aircraft delays and operating costs within the airspace caused by excessive vectoring and speed control.
c. An ability to effectively control an increased level of traffic within the sector.
d. Increased ATC productivity.
e. Increased margin of safety.
f. Reduced task-induced stress for controllers.

4.1.2 Newark Area Satellite Arrivals.

Beyond the primary jet feeder and final arrival positions at EWR, the Newark area includes satellite arrival positions. The MUGZY position controls the majority of turboprop commuter traffic arriving at EWR for landing on the overflow runway (normally Runway 11). MUGZY also controls arrivals at the nine satellite airports within the area. These include Teterboro (TEB), Morristown (MMU), Caldwell/Essex County (CDW), Lincoln Park (N07), Aeroflex/Andover (12N), Hackettstown (N05), Greenwood Lake (4N1), Sussex (FWN) and Blairstown (1N7). In addition, MUGZY is the final authority for aircraft departing MMU, CDW, and N07, approves releases for departures from the remaining satellites (except TEB), and controls overflights to other areas within the TRACON.

Figure 2 presents a simplified map of MUGZY and shows the major traffic flows within the airspace. Under most conditions, approximately 40

MUGZY Sector

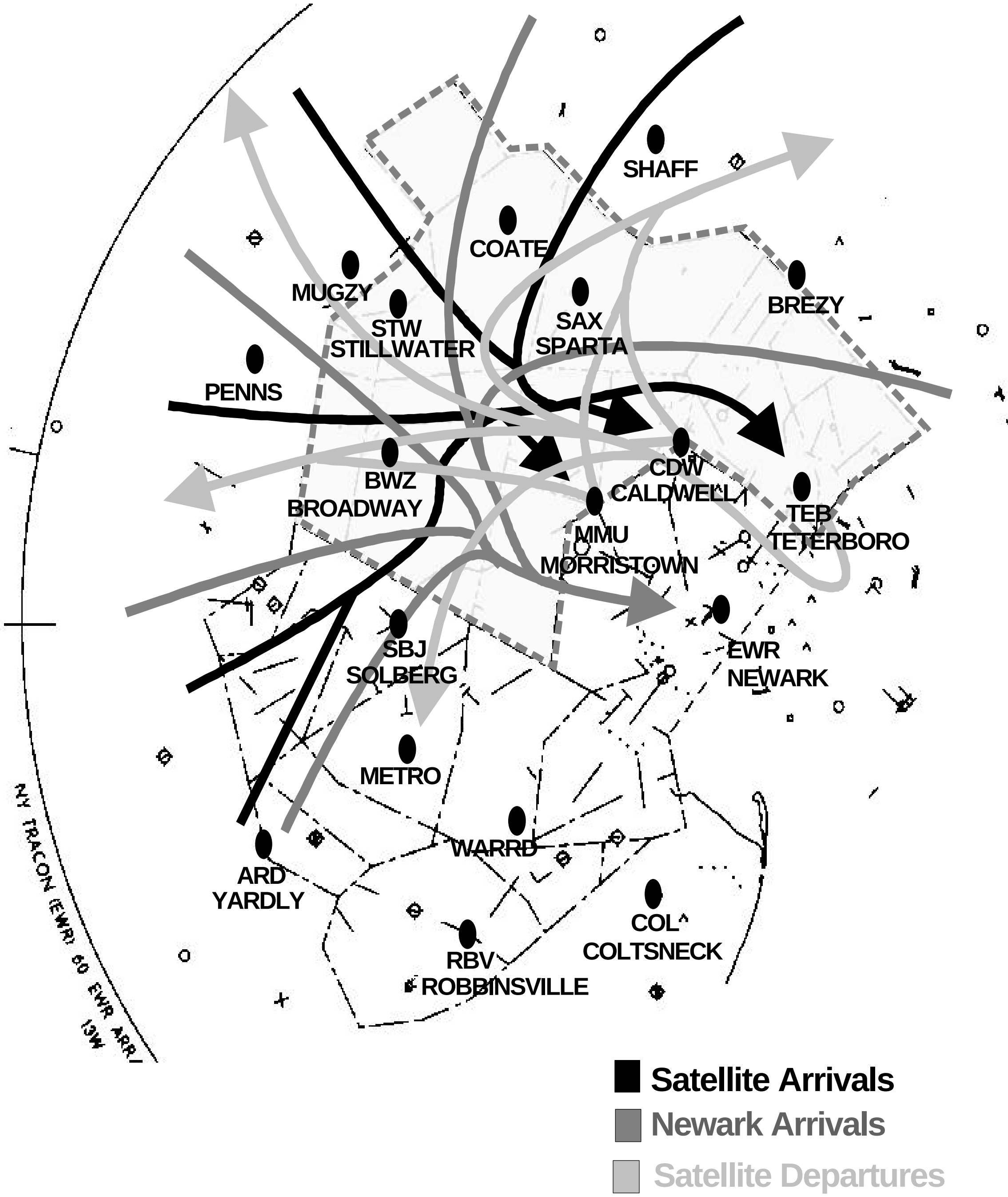

FIGURE 2. NEWARK AREA SATELLITE ARRIVAL AIRSPACE

percent of MUGZY traffic consists of turboprop commuter arrivals to EWR, with an additional 40 percent made up of arrivals of propeller and jet aircraft at TEB. The remaining 20 percent of MUGZY traffic includes arrivals and departures at the other satellites, and overflights. Under Instrument Meteorological Conditions (IMC), Runway 11 is unavailable at EWR, and MUGZY hands off the turboprop arrivals to the feeder or final position for landing on Runway 04 or 22, depending on which is the currently active runway.

Traffic peaks at MUGZY coincide with the airline jet arrival pushes at EWR as commuter turboprops arrive with passengers to support hubbing operations. During these periods, the MUGZY controller must sequence aircraft to land on Runway 11 while observing varying arrival spacing restrictions that may be imposed by the EWR Tower. The workload of this task can be compounded by demands to control arrivals at the satellite airports, release and control departures from the satellites, and control overflights.

The ATC problems presented by this satellite arrival airspace differ from those presented by the jet arrivals. While traffic volumes often are not as high, the MUGZY controllers are faced with diverse responsibilities and complex ground coordination requirements that can force them to prioritize service. For example, satellite arrivals and departures may be delayed in order to efficiently sequence the EWR turboprop arrivals. Alternatively, spacing of the EWR arrivals may suffer as the controller attends to initial contact calls, coordination requirements, and satellite operations.

The hypothesis that was tested in experiment 3 of this study was that the addition of Data Link to the MUGZY position would improve communications capacity and accuracy, thereby enhancing the controller's ability to attend to simultaneous EWR Runway 11 arrivals and satellite operations. As in experiments 1 and 2, the primary predicted effect of this improvement on controller procedures would be a shift of nontime-critical messages to Data Link. These were expected to include transfer of communication messages, initial contact calls from aircraft entering the airspace, and initial control clearances to flights bound for the various airports. The resulting reduction in frequency congestion was expected to make the voice channel more available for issuing required tactical control clearances in a timely manner. Data Link was also predicted to reduce the incidence of miscommunications requiring repetitions and corrections that further occupy the voice frequency and threaten system safety.

The indirect benefits that were hypothesized to be associated with these improvements were:

a. More timely and efficient service to the aircraft arriving at EWR and satellite airports.

b. Increased ATC productivity.

c. Increased margin of safety.

d. Reduced task-induced stress for controllers.

4.2 TEST FACILITIES.

4.2.1 ATC Facilities.

The experiments that were performed for this study were conducted in ATC simulation facilities located at the FAA William J. Hughes Technical Center. The specific laboratory configuration for the study used three primary components of the FAA Technical Center facilities: the NAS terminal laboratory; the Target Generation Facility (TGF); and the Data Link laboratory (figure 3).

The NAS terminal laboratory houses the ARTS IIIE system that performs terminal NAS data and radar processing. Version 6.04 of the ARTS IIIE operational program, modified to accommodate Data Link communications, was used for the study. Version 6.04 represents the FAA's first step toward the completely upgraded terminal ATC computer system that is targeted for possible Data Link implementation. Version 6.04 contains hardware and software upgrades including the Motorola 68040 Central Processing Unit (CPU) card, conversion to "C" language for the CPU, and an improved communications local area network (LAN). These modifications do not affect the user interface of the system and were transparent to New York TRACON controllers who, at the time of the study, were using an earlier version of the ARTS IIIE.

The ARTS communicates with several suites of the Full Digital ARTS Display (FDAD) controller workstations that are used to display radar and system data and to enter system inputs. The laboratory appearance is identical to an operational control area and includes a full voice communications system.

The NAS terminal laboratory is linked to the TGF which permits the ARTS and the controller workstations to act as a functioning control facility by providing simulated radar data and a means for interaction between aircraft and controllers. The TGF includes a laboratory in which pseudopilots operating from specialized computer terminals can carry out voice and Data Link communications with controllers and make inputs to realistically maneuver aircraft in response to ATC clearances. In addition, the TGF can be linked to remotely located, full fidelity aircraft flight

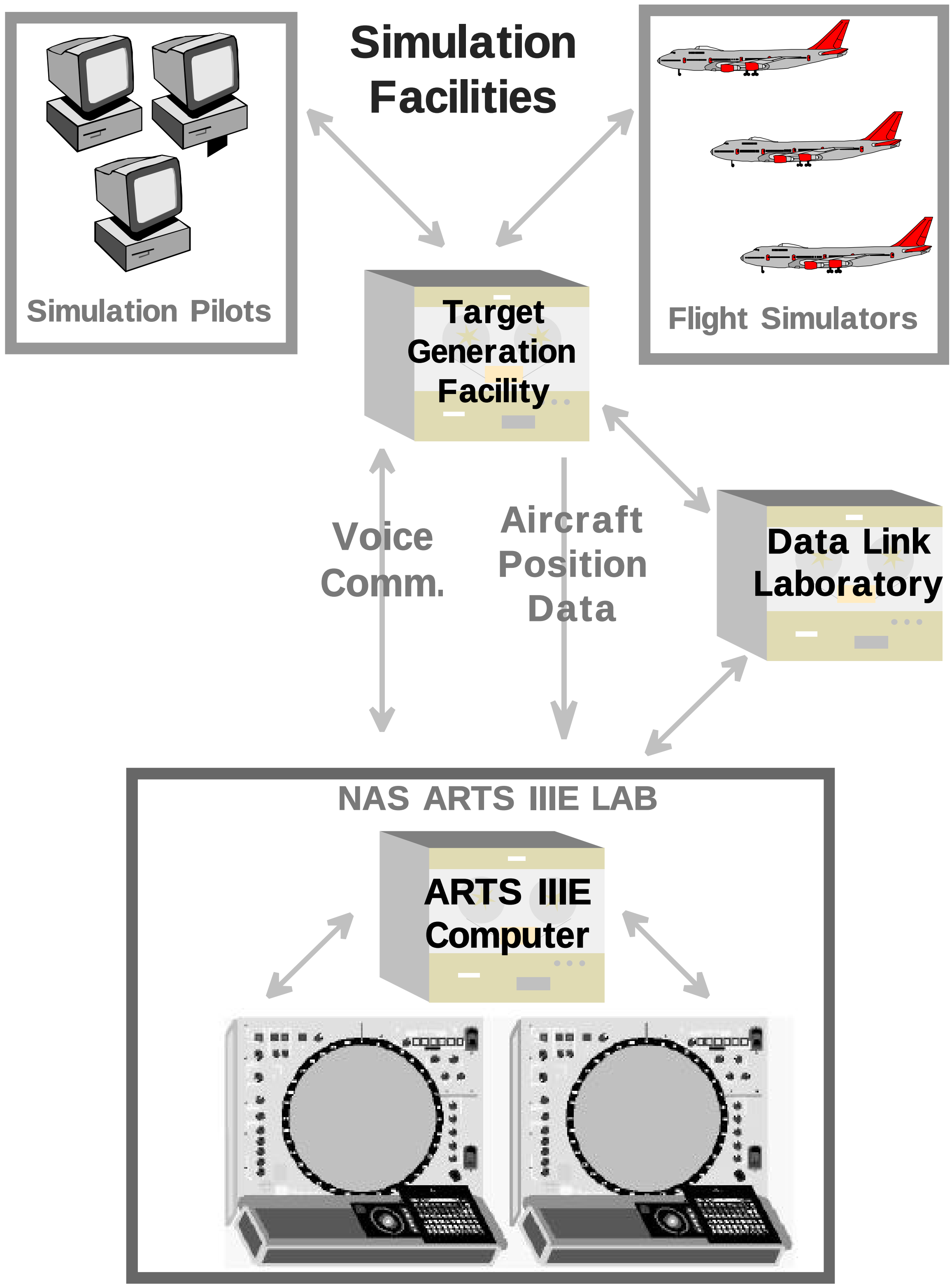

FIGURE 3. ATC SIMULATION FACILITIES

simulators in order to permit certified pilots to participate in air traffic scenarios.

Intensive pseudopilot training and technical improvements to the TGF were introduced for this study to enhance the fidelity of simulation. Pseudopilots received specialized training with the Newark area airspace and the types of messages that could be expected during the test. Additionally, the pseudopilots were provided with a synthetic radar display to improve their situation awareness, and the voice communications system was modified to realistically simulate background noise and the impact of simultaneously keyed microphones. In comparison to the en route benefits study, these measures significantly improved the quality of simulation when pseudopilots responded to voice radio clearances.

For the present experiments, the Continuous Data Recording (CDR) tapes generated by the ARTS computer during field operations were used to collect data on aircraft position and time variables. Voice communications were recorded on a 20-channel, time synchronized audio tape recorder.

The Data Link laboratory houses a Sun workstation which acts as an emulation of the future ground Data Link applications processor. The computer supports all Data Link communications among controllers in the NAS terminal laboratory, TGF pseudopilots, and aircraft flight simulators. This system also collected all data on Data Link usage by the test controllers.

4.2.2 ATC Equipment and Scenario Validation.

The primary function of the FAA Technical Center simulation facilities is to support the analysis and testing of ATC problems that arise during ongoing field operations. Because of this, the test hardware and software are identical to those used in NAS operations. For the purposes of the present study, this direct emulation capability helped to insure that the ATC scenarios and controller interfaces used in laboratory testing accurately recreated the conditions and controller work environment which existed on the baseline sample days in the New York TRACON.

Because the validity of the data collected in this study depended upon direct comparability of the operational and test environments, personnel from the Newark area were asked to evaluate the fidelity of the simulation. Prior to the study, controllers who were qualified at each of the test control positions participated in exercises to examine position equipment layouts and control traffic in the test scenarios. At the conclusion of the effort, they were asked to provide input regarding required changes to the hardware configuration, the airspace adaptation, and any other factors which may have affected the quality of the simulation. Data collection for the study began only after these individuals certified that the facilities and traffic scenarios were comparable to their counterparts at the New York TRACON.

4.2.3 Flight Simulation Facilities.

A majority of the aircraft targets in the ATC test scenarios that were used for this study were controlled by pseudopilots operating from the TGF at the FAA Technical Center. In addition, a subset of the aircraft tracks in the test runs were represented by high fidelity aircraft simulators flown by qualified professional aircrew.

Two flight simulators, a B747-400 and a B777, located at the Boeing Airplane Systems Laboratory in Seattle, WA, participated in the study. Pilot-controller communications were provided via the TGF and Data Link Laboratory and by simulated two-way VHF voice radio and Data Link. As in an operational environment, the pilots could hear all radio communications occurring on the frequency. The fidelity of the communications simulation was very high.

Both simulators were equipped with a functioning Traffic Collision Avoidance System (TCAS). Real-time TCAS targets were sent to the simulators from the TGF at the FAA Technical Center and appeared on the aircraft displays along with targets appearing “out the window” on the simulators’ visual systems. The visual targets were correlated with the TCAS display targets and provided a realistic simulation from the pilot’s perspective.

The B747-400 simulator used a certified FANS Data Link hardware and software system that was identical to the system currently installed in operational B747-400 aircraft. Figure 4 shows the B747-400 flight deck. The pilot interface in the B747-400 is hosted on the Flight Management Computer (FMC) and uses the Computer Display Unit (CDU) for display output and keyboard input. The full functionality of the system was available for this study. Receipt of an uplink is annunciated to the pilots by a single chime and a memo message (“ATC MESSAGE”) presented on the Engine Indication and Crew Alerting System (EICAS) display. The pilot selects a special function key (“ATC”) on the CDU keypad to display the uplink on the CDU.

The pilots were briefed on suggested Data Link procedures for use in the B747-400 and the B777 (see table 1), but were encouraged to try alternatives as well. In the B747-400 simulator, the suggested pilot procedure for responding to an uplink required the non-flying pilot to read

747-400 CDU Implementation

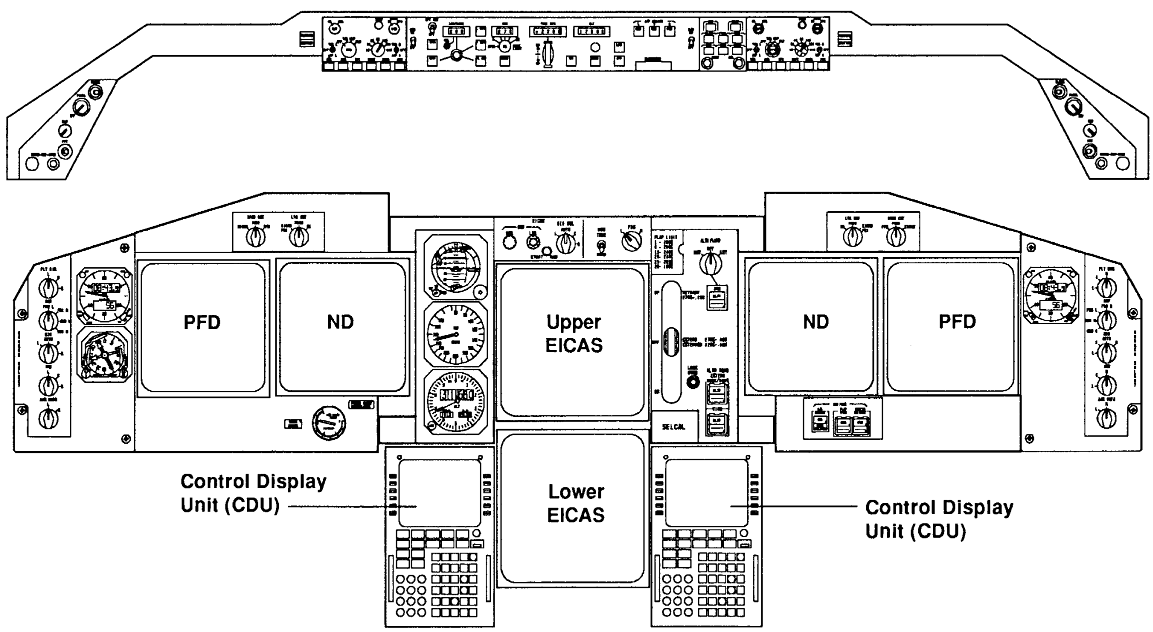

FIGURE 4. B747-400 SIMULATOR FLIGHT DECK

the message aloud to the flying pilot. The flying pilot would verbally acknowledge and fly the airplane to comply with the clearance. The non-flying pilot then accepted the message by choosing the "ACCEPT" prompt on the CDU uplink page which displayed the "VERIFY RESPONSE" page on the CDU. This page displayed the downlink response (normally WILCO in this study) as specified in RTCA DO-219 (RTCA, 1993) for the uplinked message. After verifying that the response was correct, the non-flying pilot would select the "SEND" prompt to downlink the response to the controller.

The B777 simulator used simulated ATC Data Link hardware and software which emulated a system that is scheduled to be certified in late 1996. The simulated system was modified for this study to permit only the ACCEPT/REJECT response options. The pilot was able to respond to uplinks, but was not able to send reports or any other downlinks. Downlinks were unavailable because, at the time of the test, the actual B777 hardware was in the final development stage, but was not ready for

TABLE 1. SUGGESTED DATA LINK PILOT PROCEDURES

Event	PILOT FLYING	PILOT NOT FLYING
ATC uplink received.		Read uplink aloud.
	Acknowledge uplink content.	
	Direct ACCEPT or REJECT action.	Send: ACCEPT or REJECT (as directed)
Uplink status changes: B747: SEND prompt changes to SENDING then SENT. B777: ACCEPT / REJECT prompt changes to: ACCEPTING or REJECTING then changes to: ACCEPTED or REJECTED	If ACCEPT sent: Fly the airplane to meet the clearance. If REJECT sent: Direct PNF to establish voice radio contact with the controller.	Note receipt of: B747: "SENT" B777: "ACCEPTED" or "REJECTED" Note: If change of status is not received within TBD seconds go voice and confirm response with the controller.
	Direct CANCEL (clear the message area).	B747: Return to normal use of CDU B777: Cancel message display when directed.

use. Since limited programmer time was available to prepare the B777 simulator, only the uplink portion of the simulated system was ready for test.

Figure 5 shows the B777 flight deck. The ATC Data Link function for the B777 is part of the communication system that includes ATC and Company Data Link within the same system. When an uplink is received, the annunciation is a high-low chime accompanied by an advisory message

777 EICAS/Glareshield Implementation

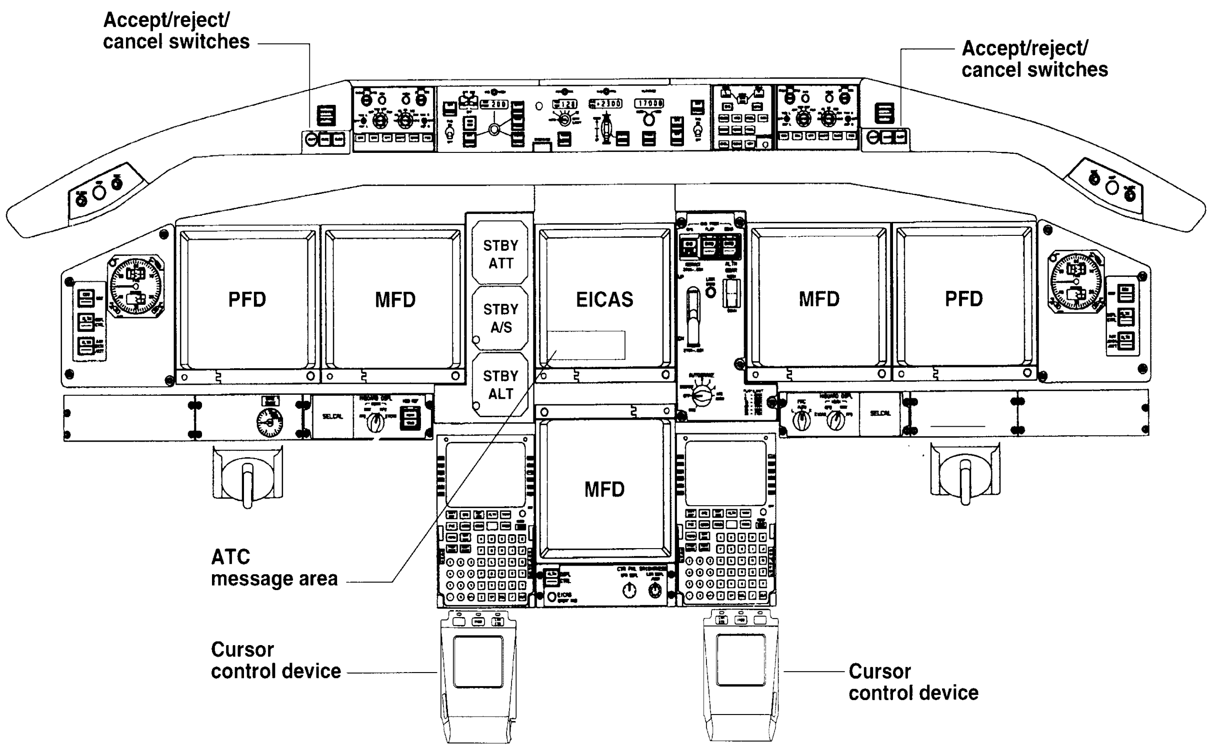

FIGURE 5. B777 SIMULATOR FLIGHT DECK

("•ATC") on the EICAS display. The text of the uplink automatically appears in a block below the engine instrument display which is capable of presenting five lines of text with up to 30 characters per line. This display was capable of presenting all uplinks used during the test. An alternative method for viewing an uplink is also available. To use this method, the pilot chooses the "COMM" function on the lower Multifunction Display (MFD), which then presents the text on the MFD.

Responses to uplinks are made by pressing "ACCEPT/REJECT" buttons mounted on the glare shield in front of both pilots. Alternatively, the pilot may respond by selecting the "ACCEPT" or "REJECT" prompt on the lower MFD. During this test, the pilots used the glare shield buttons almost exclusively because of their convenience.

The suggested pilot procedure for this study required the non-flying pilot to read the uplink aloud to the flying pilot (see table 1). The flying pilot would acknowledge verbally and fly the airplane to comply with the clearance. The non-flying pilot would then accept the message by choosing the “ACCEPT” button on the glare shield. This action sent the appropriate downlink response (normally WILCO for this test) to the uplink as specified in DO-219.

4.3 DATA LINK PERFORMANCE, SERVICES, AND AIRCRAFT EQUIPAGE LEVEL.

The Data Link message transaction times for these experiments were controlled by the Data Link laboratory equipment. One-way transmission times were programmed to meet the near-term requirements for terminal Data Link performance specified by the FAA’s Data Link Operational Requirements (FAA, 1995). The duration of each uplink and downlink transmission delay was randomly drawn from a rectangular distribution with a minimum of 4 seconds, a maximum of 6 seconds, and a mean of 5 seconds.

During testing, pilots and controllers had the capability to send and respond to a range of Data Link ATC messages. The message set conformed to the standards defined in DO-219. The set included transfer of communication messages, as well as manually composed altitude, speed and heading clearances. Initial contact messages were downlinked from the equipped aircraft. Terminal information messages, as well as commonly-used clearances, were tailored to the test control positions and stored for rapid access by menu selection. In addition to the initial contact altitude report, available pilot downlink responses to controller messages included ROGER, WILCO, UNABLE, and STANDBY options.

The call signs, flight plans, and types of aircraft that were used in the test scenarios for the three experiments were identical to those recorded on the sample day CDR tapes obtained from the New York TRACON. In those test runs where additional aircraft were inserted into the original scenarios, actual flights into the New York TRACON that had been delayed for various reasons on the sample day were placed in the arrival stream at realistic positions and times. Winds aloft in the simulation test scenarios were matched to the sample days based on records provided by the National Oceanic and Atmospheric Administration (NOAA).

To simulate a fully implemented system, approximately 90 percent of the aircraft in each scenario used in the three primary experiments were equipped to conduct Data Link ATC communications in addition to voice radio communications. In order to realistically portray likely equipage schedules, the 90-percent equipage level was achieved by assigning Data Link to the newest commercial carrier and business aircraft represented in the sample day CDR tapes.

4.4 TEST PARTICIPANTS.

4.4.1 Air Traffic Controllers.

The controller subjects for the three experiments were nine Full Performance Level (FPL) terminal ATC specialists recruited from the New York TRACON. Each group of three controllers was accompanied by an ATC supervisor. Participation was limited to controllers and supervisors who regularly staff the feeder and final arrival positions (experiments 1 and 2), and the MUGZY position (experiment 3) within the Newark area of the TRACON.

4.4.2 Aircrews.

Twenty-four pilots participated in the study. These included Boeing Flight Test Pilots, Boeing Training Pilots, FAA pilots, and airline pilots. All pilots were rated as captains in the B777 and B747-400 with three exceptions. Of these, two were not rated in either aircraft, and one was not rated in the B747-400. The lack of a current rating for these three pilots was not expected to effect the outcome of the test because of the nature of the flying presented in the test scenarios (i.e., normal procedures on approaches which did not require a detailed systems knowledge of the airplane). Furthermore, all three of these pilots always flew with a currently rated pilot during the test. Total flight hours for the pilots ranged from 4000 hours to 22,000 hours. Most of the pilots were not experienced in flying within the Newark area of the New York TRACON.

Participation of the Boeing simulators occurred during experiments 1 and 2 of the study. All pilots flew both the B747-400 and B777 simulators. A crew typically flew one of the simulators on three consecutive test runs, and then flew the other simulator for three runs. To provide experience with the duties of the pilot flying and pilot not flying, the crews rotated positions between runs. In addition, all pilots hand flew (did not use auto pilot) on at least one flight in each simulator to permit evaluation of the Data Link pilot procedures in both auto-flight and non-auto flight environments.

4.5 TRAINING.

4.5.1 Controller Training.

In order to ensure the validity of the performance data collected in this study, extensive efforts were made to accurately simulate the working environments and conditions of operational ATC facilities. As discussed previously, these efforts included the use of actual NAS equipment and subject controllers who are thoroughly familiar with the test airspace. To further guarantee representative data, an attempt was made to provide the subject controllers with a knowledge of Data Link and a reasonable level of proficiency in using the computer-human interface (CHI).

The controller subjects were trained in the use of the Data Link system in classroom sessions and participated in practice sessions in the terminal NAS laboratory. Training occurred over the first 3 days of each study session. The first day was devoted to briefings describing the Data Link displays and inputs. These were followed by an initial laboratory practice session during which facilitators were available for assistance. The remaining training days were composed of practice sessions in which operational training scenarios from the Newark area were used. The traffic loads of the scenarios were raised progressively from 80 percent to 110 percent. Training at the feeder, final, and MUGZY positions was equalized by rotating the controllers after each training scenario run. The final training day included classroom instruction on the rating and questionnaire instruments that were used during testing.

A Data Link training manual was provided to the subjects for use in classroom sessions. Laboratory training days began with a discussion period during which any questions on Data Link operation were addressed. Each controller received a total of 12 hours of laboratory practice prior to the start of data collection. All simulated aircraft were equipped with Data Link during early training sessions to focus on basic practice with the new communication medium. Later sessions reduced aircraft equipage to the level that was used during testing in order to permit practice alternating between voice and Data Link usage.

The later practice sessions used ATC scenarios which presented air traffic demands that are similar to the test scenarios in terms of the general pattern of arrival at the sector boundaries, mix of aircraft types, and call signs. Thus, during the training phase of the experiment, the controllers experienced demands representative of daily variations at the test positions. However, to avoid bias attributable to anticipation of a specific traffic pattern, the configurations of air traffic arriving at the positions that were dictated by the sample day CDR tapes were presented only during actual testing.

Procedures for application of Data Link to the control problems presented by each test position were considered during discussions that were interspersed with the training sessions. However, no fixed procedures were dictated by study support staff. Consequently, strategies for dividing different message types between voice and Data Link and selecting useful messages for uplink via the menu functions varied among controllers. In addition, where a handoff controller was available for the position, or where the supervisor could assist a controller, the controller at the radar position was permitted to adopt an individual approach to sharing Data Link tasking.

4.5.2 Aircrew Training.

All pilots received a pretest briefing in small groups. This briefing consisted of viewing a video describing the FAA Data Link program, followed by an overview of the test objectives, test setup, flight scenarios and airspace, and simulator techniques. The pilots also received classroom instruction on Data Link operations and a demonstration of Data Link in each simulator. The demonstration for pilots who participated in the last four test sessions contained special emphasis on the CONFIRM ASSIGNED ALTITUDE uplink in the B747-400 because of the complicated nature of the required response.

The pilot training provided in this study was abbreviated for two primary reasons. First, because of the limited past work in high fidelity simulation of Data Link in the terminal environment, there was little experience available to draw upon as a basis for creating a realistic training course. Second, there was no training facility available to simulate the time-compressed nature of Data Link communications sent by experienced controllers. This prevented the introduction of effective practice in dealing with these messages in the simulators. Therefore, pilot proficiency in the use of Data Link increased over the first few flights.

4.6 TESTING METHODOLOGY.

The study included three experiments which were conducted concurrently over three 7-day sessions. A session consisted of a full replication of each experiment, with three controllers and an area supervisor participating in the Newark Jet Arrivals testing (experiments 1 and 2), and the Newark Satellite Arrivals testing (experiment 3).

4.6.1 Simulation Scenarios.

Two baseline simulation scenarios were created as test conditions for experiments 1 and 2. Newark area personnel were asked to select two recent historical sample periods for the jet arrival positions. In one of these, jet arrivals to EWR had been temporarily denied entrance to the area because of traffic saturation in the feeder/final airspace. During the second period that was selected, jet arrival holding had not occurred, but arrival rush traffic was considered to be within a normal range. The selected dates were November 28, 1995, and March 12, 1996, respectively, for the two samples. Similarly, for experiment 3, a sample rush period (February 5, 1996) was selected as representative of typical operations for the satellite airports and for commuter arrivals to EWR. None of the selected sample periods were affected by adverse weather conditions other than high wind velocity. Wind velocities were accurately recreated in the test scenarios.

The three CDR tapes from the sample periods were used to generate the baseline test scenarios for simulation testing. In experiment 1, the test scenario was identical to the baseline sample period in which flight holding had occurred. Because no holding had occurred during the historical baseline sample periods for experiments 2 and 3, these test scenarios were supplemented with additional aircraft to increase traffic load.

This manipulation was introduced to increase the sensitivity of the voice - Data Link comparison. Significant differences between the capabilities of the voice channel alone and the system expanded with Data Link should emerge when traffic volume and correlated communications requirements are high. Thus, aircraft were added to the scenarios in an effort to present realistic traffic demands which were at least as high as those which had prompted flight holding on the historical baseline day tested in experiment 1.

In both cases, the added aircraft were composed of actual flights that had been scheduled for arrival during the sample periods, but had been delayed for various reasons. Two versions of each added-traffic scenario were created to control for the effects of repeated testing under voice-only and voice plus Data Link conditions. The two scenario versions presented identical spatial and temporal patterns of arrivals at the area boundaries. However, the call signs of similar aircraft types were reassigned to control for learning effects.

The scenario for experiment 3 was based on an historical sample period during which the MUGZY radar position was supplemented by an assistant controller (handoff controller). This level of staffing was replicated during testing. In addition, as in the operational situation during heavy traffic periods, the controller staffing the final position in experiment 2 was permitted to request assistance from the observing supervisor during both voice-only and Data Link test runs. For the Data Link runs, this assistance could include sending Data Link messages. In order to duplicate the conditions of the historical baseline day, assistance from the supervisor in experiment 1 was limited to normal flight strip management duties, ground communications, and monitoring of the traffic situation.

4.6.2 Study Design.

- Experiment 1

During each session of the study, data collection for experiment 1 occurred over three test runs. In these runs, each of the three subjects controlled traffic in one test run at the jet arrival feeder position and one test run at the jet arrival final position. Because comparable operational data under voice-only communications were derived from the historical CDR tape for November 28, 1995, all three runs were completed with both voice radio and Data Link communications available to the subjects. The 50-minute scenario included 48 flights. During testing, the controllers and supervisors had the option to institute and modify traffic speed and miles in trail (MIT) restrictions and holding of arrivals, if required.

- Experiment 2

Data collection for each session of experiment 2 occurred over six 57-minute test runs. In these runs, each of the three subjects controlled traffic at each of the jet arrival positions in two test scenarios where traffic was increased by 10 aircraft over the 55 represented on the baseline CDR tape for March 12, 1996. Since no comparable operational data were available for this modified scenario, one of the test runs for each subject at each position was conducted under voice communications alone, while the other was conducted with both voice radio and Data Link available. As noted earlier, the two scenarios varied call sign assignments to control for the effects of scenario familiarity on controller performance. Sequence (learning) effects for the two communications modes and the potential confounding of scenario and communication mode effects were controlled by varying the orders of presentation across the full subject sample.

- Experiment 3

Data collection for each session of experiment 3 occurred over six 45-minute test runs. Each of the three subjects controlled traffic at the satellite arrival position in scenarios derived from the baseline CDR tape for February 5, 1996. The test scenarios included the original 37 arriving flights plus six additional aircraft which were added to the traffic flow. Because no directly comparable operational data were available for the modified scenario, one of the test runs for each subject was conducted under voice communications alone, while the other was conducted with both voice radio and Data Link available.

The voice and Data Link runs for each subject were conducted with different versions of the scenario to control for the effects of familiarity on performance. As in experiment 2, sequence effects for the two communications modes and the potential confounding of scenario and communication mode effects were controlled by varying the orders of presentation across the full nine subject sample.

- Reduced Equipage and Voice Radio Initial Contact Testing

The final three test runs of each session were reserved for repeating any of the prior runs that may have been compromised by a simulation system failure. When one or more of these runs were not required in a session, they were used to examine secondary test issues. These included the effects of reducing Data Link equipage from approximately 90 percent to 50 percent of the aircraft in a scenario, and the impact of eliminating the Data Link initial contact capability from the message set. The jet arrival scenario from experiment 1 was used for this testing.

- Testing Sequence

A schedule specifying the sequence of testing was created to permit efficient use of aircraft simulators and to accommodate rest breaks for the controller subjects. The sequence variation across test sessions also reflected efforts to control for order of testing (learning) effects. The counterbalancing scheme for experiments 2 and 3 resulted in roughly equal numbers of subjects experiencing the voice only mode and the Data Link mode on the first trial. Within each of these sequences, an approximately equal number of subjects experienced the two scenario versions on the first and second trials.

In order to prevent incidental learning of the test scenarios through observation, only those subject controllers who were participating in a particular test run were allowed to be present in the simulation facilities during the run.

4.7 MEASURES.

4.7.1 Criterion Safety Measures.

The measures discussed below were collected in all three experiments of this study to insure that any improvements in the efficiency of operations that yielded a user benefit were not achieved at any loss in system safety.
Three groups of measures were used as primary criteria for determining whether the ATC activities and aircraft operations observed during a test run were accomplished in a safe fashion. Failure to pass any one of the criteria resulted in rejection of the performance data for a test run. These measures were selected as criteria because they are essentially identical to those

currently used in the operational ATC environment to identify potentially unsafe operating conditions and performance failures.

- Supervisory Safety Evaluation

When working in the TRACON control room, supervisors, who are familiar with all aspects of area operation, oversee controller actions and air traffic activity to ensure operational safety. The supervisor uses expert judgment to make determinations of potentially unsafe conditions and to take measures to correct the problem.

This operational assessment technique was employed in the present study as the primary indicator of safety. The observing supervisor judged the safety of each test run by completing two items on the supervisory questionnaire (see appendix B). The first item was used to determine whether the supervisor observed any aircraft separation violations that would have constituted an operational error. The second item solicited a comprehensive judgment of the margin of safety that was maintained during the test run. For operational errors, test personnel, controller subjects, and the observing supervisor made a group determination of the cause of any error. If the separation violation was determined to be caused by a controller error, the test run was judged invalid.

- Controller Safety Evaluation

In addition to supervisory monitoring, it is common practice in field ATC operations for controllers to identify potentially unsafe conditions that they encounter while staffing a sector. This evaluation was formalized for the present experiments using a comprehensive controller safety judgment corresponding to the supervisor's overall judgment (see appendix B).

4.7.2 Flight Efficiency/Sector Productivity Measures.

This class of measures was used to assess variations in aircraft arrival times, speeds, and flight paths as they entered and passed through the test sectors. The purpose of these measurements was to assess aircraft operating efficiency and sector productivity as a function of the use of Data Link communications. These primary outcome measures were acquired by direct analysis of the baseline and test CDR tapes.

- Time in Problem and Distance Flown

For the following measures, problem entry points for arrivals were defined by designating a set of line segments surrounding the horizontal boundaries of the Newark area. Problem exit points were defined by flight destination. Exit points for arriving flights were defined as a point 7 miles from the landing runway.

Aircraft Time In Problem -- For each target aircraft, the elapsed time in decimal minutes recorded from entry to the problem to exit from the problem.

Aircraft Distance Flown in Problem -- For each aircraft, the distance flown in miles recorded from the problem entry point to the exit point.

Time and distance measures were calculated for each flight in the test scenarios. Summary statistics were calculated for the entire sample of flights and for individual categories of flights (e.g., Newark Jet Arrivals, Newark Overflow Arrivals, Teterboro Arrivals, etc.).

- Entry Time, Exit Time, and Arrival Time

For all flights, the entry time was defined as the clock time at which the aircraft entered the problem. For aircraft arriving at EWR and each of the satellites, the clock time at which the aircraft crossed a point 7 miles from the runway was defined as the arrival time. Arrival times were calculated for all arriving flights. The entry time measure was used to detect differences in aircraft delay caused by holding or restrictions. The arrival time measure was used to calculate total arrival delays and as a basis for assessing sector productivity for the full flight sample.

- Analysis of Flight Path Records

The time and distance measures discussed above cannot reveal control strategies that were used to achieve specific time and distance results. In order to validate apparent differences in these measures between test conditions, data visualization tools were applied to the CDR tapes to extract horizontal and vertical profile tracks for the test runs and for the baseline days. The plots were used to detect holding patterns and vectoring actions.

4.7.3 Communications Measures.

In addition to direct measures of performance, indicators of precursors to the benefit measures of interest were collected as secondary outcome metrics. The study was based on the premise that adding Data Link to the existing voice radio would expand the controller's communications capacity, thereby permitting them to more efficiently handle aircraft in sectors saturated because of communications problems. Thus, any benefit that was measured should have been correlated with a redistribution of ATC communications among the two channels. The following measures were used to determine the manner in which the test controllers used Data Link and voice to accomplish their communications tasks.

- Number, Duration, and Content of Voice Messages

The frequency with which the test controllers and simulation pilots used the voice radio channel was measured by counting the number of messages contained in transcripts of the voice recordings made during the test runs and those obtained from the New York TRACON for the historical baseline days. The time spent by the controllers and simulation pilots communicating on the voice channel was measured by manual timing of the messages on the test and sample day audio recordings.

The content of the voice messages sent by controllers during the test runs and on the sample days was assessed by reviewing the voice tape transcripts. Messages were tabulated by message category. These categories included: (1) individual speed, heading, and altitude clearances; (2) combined clearances; (3) transfer of communication messages; (4) responses to initial contact calls; (5) informational messages; (6) route changes; and other messages, as required.

- Number and Content of Data Link Uplinks Sent

The number and content of Data Link messages sent by controllers was assessed by analyzing the CDR tapes from the test runs. Messages were tabulated by message category. These categories included: (1) individual speed, heading, and altitude clearances; (2) combined clearances; (3) transfer of communication messages; (4) responses to initial contact downlinks; (5) informational messages; (6) route changes; and other messages, as required.

- Data Link Transaction Time

To provide an overall index of the Data Link performance under which the benefit results were obtained, the duration of each Data Link transaction occurring during testing was measured. Total transaction time was defined as the elapsed time between the initiation of an uplink command by a controller to the receipt and display of an aircrew response. Total transaction times were recorded to the nearest second.

4.7.4 Controller Measures.

This group of measures includes indices used to detect variations in the quality of sector performance and controller states of high workload or task-induced stress that may be associated with ATC task complexity or the communications mode(s) available for air-ground communications.

- Supervisor Ratings of Sector Performance

Following each test run, the supervisors were probed on several factors which underlie their expert evaluations of workload and sector performance in the field. Because of numerous mitigating factors, subjective evaluations were used to measure these variables with the supervisor acting as an "expert filter." In questions preceding the overall safety judgment on the supervisor's questionnaire, the supervisors were asked to judge the extent to which each of the following events occurred during the run:

a. Errors or Omissions in Required Flight Strip Marking
b. Untimely Issuance of Clearance
c. Failure to Comply with Letters of Agreement
d. Early Handoff Offers
e. Late Handoff Offers
f. Delayed Handoff Acceptance
g. Untimely (late) Issuance of Transfer of Communication Message
h. Failure to Meet MIT Restrictions

For each of the above, the questionnaire permitted the supervisor to indicate that the event (1) never occurred, (2) occurred, but within normal limits of operational acceptability, (3) occurred more often than normal for this sector under heavy traffic demands, or (4) occurred unacceptably often. They were also asked to comment on perceived causes for any negative judgment.

- Controller Workload Ratings

Controller workload was assessed using three perceived workload rating scales. The first scale solicited an absolute rating of the workload that the controller experienced during the test run using the Subjective Workload Assessment Technique (SWAT). SWAT was developed in the early 1980's by the US Air Force as a standardized method for obtaining quantified estimates of perceived workload in a broad variety of tasks. The SWAT scales permitted the controller to assign ratings on three underlying dimensions of workload: time, mental effort, and stress. Each dimension could be rated on a 1 (low) to 3 (high) scale.

In SWAT, the three ordinal ratings for a work period are converted to an overall interval workload scale ranging from 0 (low workload) to 100 (high workload). The interval scale used to interpret the ordinal ratings is generated using conjoint measurement analysis of an individual's concept of how the time, effort, and stress dimensions combine to produce different workload levels. In this study, each test controller provided this information during the training phase by ranking the three dimensions in terms of their importance to producing workload while controlling traffic.

The second scale required a relative rating of workload. The controller was asked to rate the previous work period in comparison to a corresponding busy work period at the test position in the appropriate sector in the Newark area. The test run workload was rated as (1) much lower than usual, (2) somewhat lower than usual, (3) about the same, (4) somewhat higher than usual, or (5) much higher than usual.

Finally, the controller was asked to make a binary judgment of the workload experienced during a test run. The controller indicated whether the workload was “acceptable and presented no threat of resulting in performance failure” or “unacceptable and threatened to, or actually did, affect the quality of my performance.”

Because no comparable data for the historical baseline day were available, the SWAT measure was not used for the test runs of experiment 1.

- Subsidiary Measures

Two additional measures were used to meet subsidiary human factors objectives of this study. Following each test run, supervisors at each sector were asked to report on errors in Data Link keyboard inputs. If any errors were observed, the supervisors were asked to describe how the errors were resolved (see appendix B).

In order to obtain information on how sector tasking and communications were distributed among the sector personnel in experiments 2 and 3, the radar controller and the handoff controller or supervisor completed a duty profile after each test run. The profile required the two controllers to indicate the frequency with which they performed each of 13 sector tasks during the previous test run (see appendix B).

- Post-test Questionnaire and Debriefing

Following completion of all test trials within a session, the subject controllers and supervisors completed a post-test questionnaire and participated in a group debriefing. The questionnaire and debriefing were used to solicit comments from the group regarding the fidelity of the simulation, the perceived effectiveness of Data Link, the Data Link CHI, and Data Link’s projected effects on controller tasking and the ATC system. The post-test questionnaire is included in appendix B.

4.7.5 Aircrew Measures.

Pilots completed a questionnaire following each test run to assess their immediate impressions of the flights. The pilots also completed a post-test questionnaire at the end of their 8-hour participation in the study to provide general evaluations of Data Link.

A cockpit observer was present in the simulator during all flights. The observer recorded the number of Data Link and voice transmissions as they occurred. The observer also rated Crew Resource Management (CRM) during the flights, and completed a questionnaire on the effectiveness of Data Link communications.

Audio and video recordings were obtained for each flight. One channel of the audio was the output from the simulator cab audio system which included all voice transmissions on the selected frequency. The other channel captured flight deck audio using two lapel microphones mounted close to the pilots. The four-view split screen video recorded a wide-angle view of the flight deck, a closer view of the Mode Control Panel, the EICAS display (B777 only), MFD display (B777 only), right CDU, and left CDU (B747-400 only).

5. RESULTS.

5.1 EXPERIMENT 1 -- COMPARISON OF DATA LINK TESTING TO HISTORICAL VOICE-ONLY EWR JET ARRIVAL DATA.

Experiment 1 was conducted to provide a direct comparison of actual operational performance in the Newark area jet arrival airspace under current voice-only communications to test performance with both Data Link and voice radio communications available to the controllers. The 50-minute Data Link test scenario presented a temporal and spatial pattern of flights that was identical to that experienced by controllers on the historical baseline day. The primary Data Link benefit hypothesized for this experiment was an ability to postpone or eliminate the air traffic holding outside the Newark area that had occurred on the baseline day because of traffic volume.

5.1.1 Operational Safety Assessments.

5.1.1.1 Operational Errors.

No operational errors (minimum terminal separation violations between aircraft) were reported by the observing supervisors in any of the nine test runs of experiment 1.

5.1.1.2 Supervisor and Controller Safety Ratings.

Expert operational assessments of safety for the test runs are shown in figure 6. Mean margin of safety ratings for the feeder and final controllers as well as the observing supervisor were calculated by assigning values of 1 to 4 to ratings ranging from "unsafe" to "higher margin of safety than normal."

None of the controllers or supervisors rated any of the nine test runs as "unsafe." Three of the runs were rated by the supervisors as having a greater margin of safety than normal for the airspace in the operational, voice-only environment, while six were rated as having a normal margin of safety. Similarly, of the 18 ratings made by the feeder and final controllers, 8 indicated that the margin of safety was higher than normal, while 10

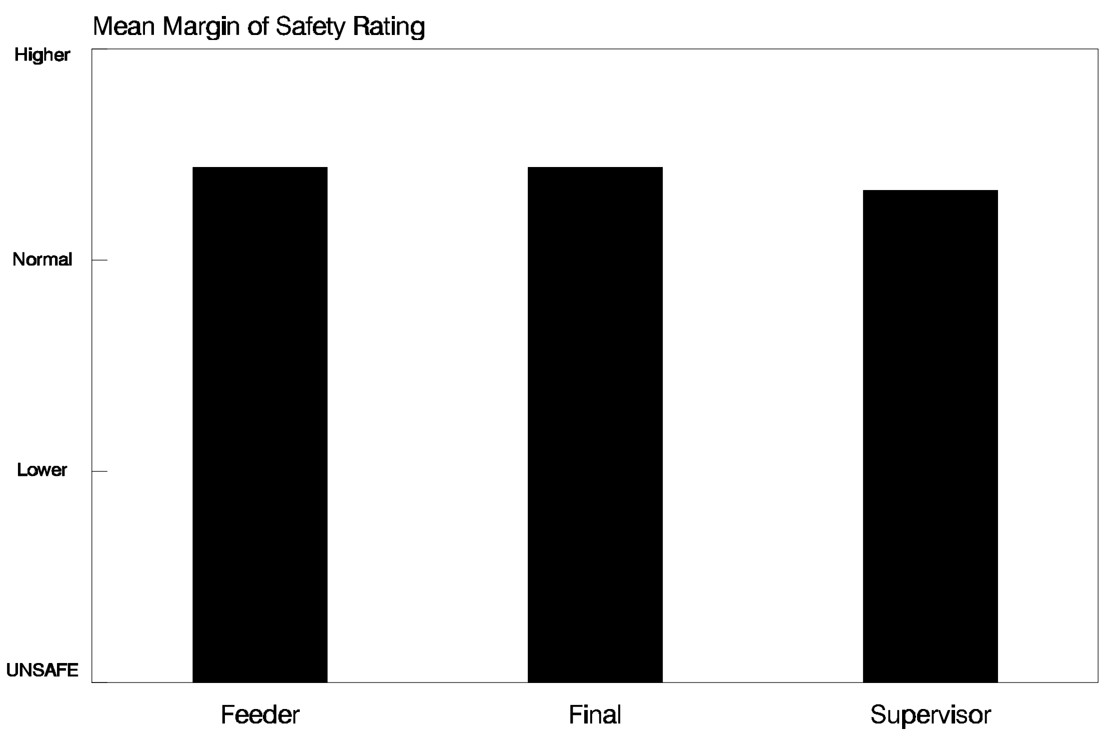

FIGURE 6. SUPERVISOR AND CONTROLLER SAFETY RATINGS IN EXPERIMENT 1

indicated that the margin of safety was normal for the sector during a similar traffic rush period in the operational environment. Overall, the mean scores suggest that the margin of safety was increased with Data Link in comparison to current operations under voice-only communications.

5.1.2 Flight Efficiency and Airspace Productivity.

The findings presented above indicate that the controllers in all nine Data Link test runs were able to safely control the baseline jet arrival traffic. The following subsections present data on changes in flight arrival delays and operational efficiency that were associated with the use of Data Link to supplement the voice radio communications channel at the feeder and final positions.

5.1.2.1 Sector Entry Time.

At terminal arrival positions, the primary tools available to control traffic volume and maintain separation are restrictions placed on aircraft at the airspace boundaries. These restrictions can be imposed and removed by controllers or supervisors in conjunction with Air Traffic Management at any time, as required by the traffic situation. Restrictions placed on flights in adjacent en route airspace can include maximum speed and minimum MIT over an arrival fix, as well as holding to completely preclude entry of additional aircraft into the terminal airspace. Each of these actions result in delays to flights in the immediate vicinity. Furthermore, these delays can cascade upstream to create ground delays and remote en route delays for flights bound for the affected airport. Conversely, when restrictions and holding are prevented or postponed, more aircraft enter the terminal airspace and the effective capacity of the system is maintained or increased.

Sector entry time was used as a measure in this experiment to capture any effect of Data Link communications on the controllers' ability to maintain traffic flow into the terminal airspace by avoiding the use of restrictions and/or holding. Sector entry delay savings or losses for each flight in a test run were calculated by subtracting the time at which the aircraft crossed the sector boundary during testing from its boundary crossing time on the historical baseline day. If a flight did not enter the sector during the 50-minute scenario period in either the historical baseline or the test runs, it was not included in this calculation. As shown in figure 7, each of the Data Link test runs yielded a mean per-aircraft delay savings over the voice-only baseline day. The mean delay reduction across test runs was 1.98 minutes per aircraft.

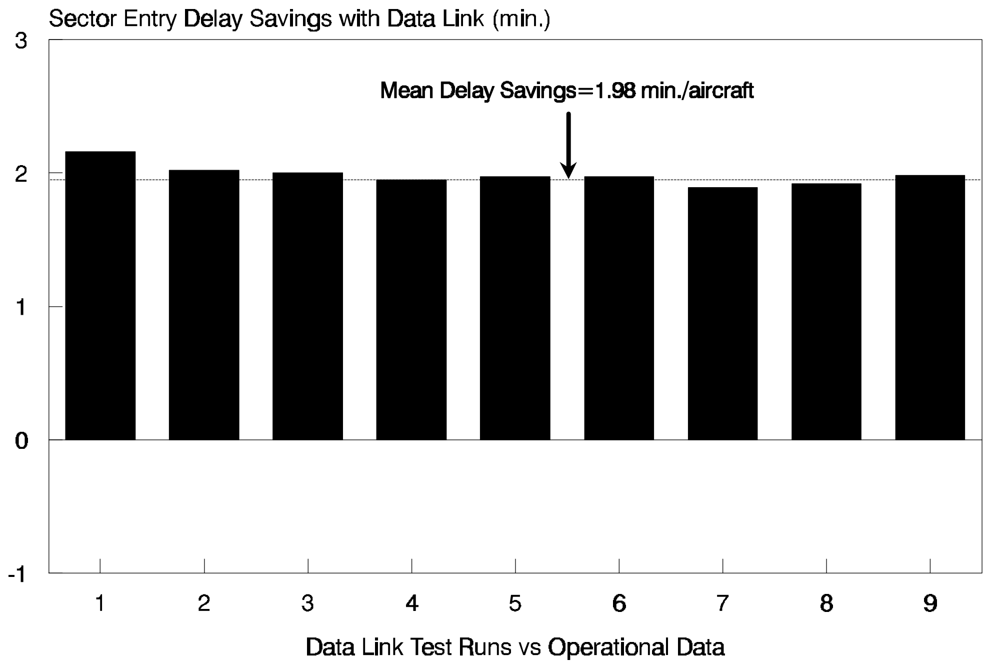

FIGURE 7. SECTOR ENTRY DELAY SAVINGS IN EXPERIMENT 1

This decrease in sector entry delay was directly attributable to differences in restrictions placed on arriving flights between the voice-only baseline day and the Data Link test trials. While flight holding was instituted by the controllers during the historical traffic rush period, no arrival holding in en route airspace was employed by the controllers during any of the nine Data Link test trials. This resulted in an average reduction in en route flight time and distance for the affected flights, and a subsequent earlier entry to the Newark area terminal airspace.

5.1.2.2 Time and Distance Flown in Sector.

Secondary methods used at terminal arrival positions for controlling inbound traffic flow and separation involve speed reductions, “S” turns, and vectoring within the terminal airspace. The utility of these methods is restricted by the limited maneuvering airspace and procedural constraints of the terminal environment. However, they can significantly contribute to the total efficiency of flight and to delays experienced by arriving aircraft.

Measures of the time and distance flown within the feeder/final airspace were used to assess any effect of the expanded air-ground communications channel on the ability of controllers to efficiently space and merge arriving aircraft as they maneuvered to the landing runway. Only those aircraft that entered the sector and landed on both the historical baseline day and during testing were included in these calculations.

Figure 8 presents the mean flight distance and time for the Newark jet arrivals that landed during the 50-minute scenario on both the historical baseline day and during Data Link testing. As shown in the figure, the average arrival on the historical baseline day flew approximately 60 miles within the feeder/final airspace over a period of approximately 17 minutes. During Data Link testing, the mean flight distance for an aircraft dropped to approximately 54 miles, while flight time was reduced to approximately 14 minutes, for an average per-aircraft savings of 6 miles and 3 minutes. Statistical comparison of the historical baseline and test data revealed that the reduction in flight time with Data Link were significant ($t_8=5.96$, $p<.001$).

5.1.2.3 Flight Arrival Delay.

The combined effects of sector entry delays and flight times within the sector that are created by terminal ATC actions are ultimately reflected in the arrival time of each aircraft at the destination airport. Arrival delay savings or losses for each flight in a test run were calculated by subtracting the time at which the aircraft crossed the problem exit point for the landing runway during testing from its crossing time on the historical baseline day. Only those aircraft that entered the sector and landed on

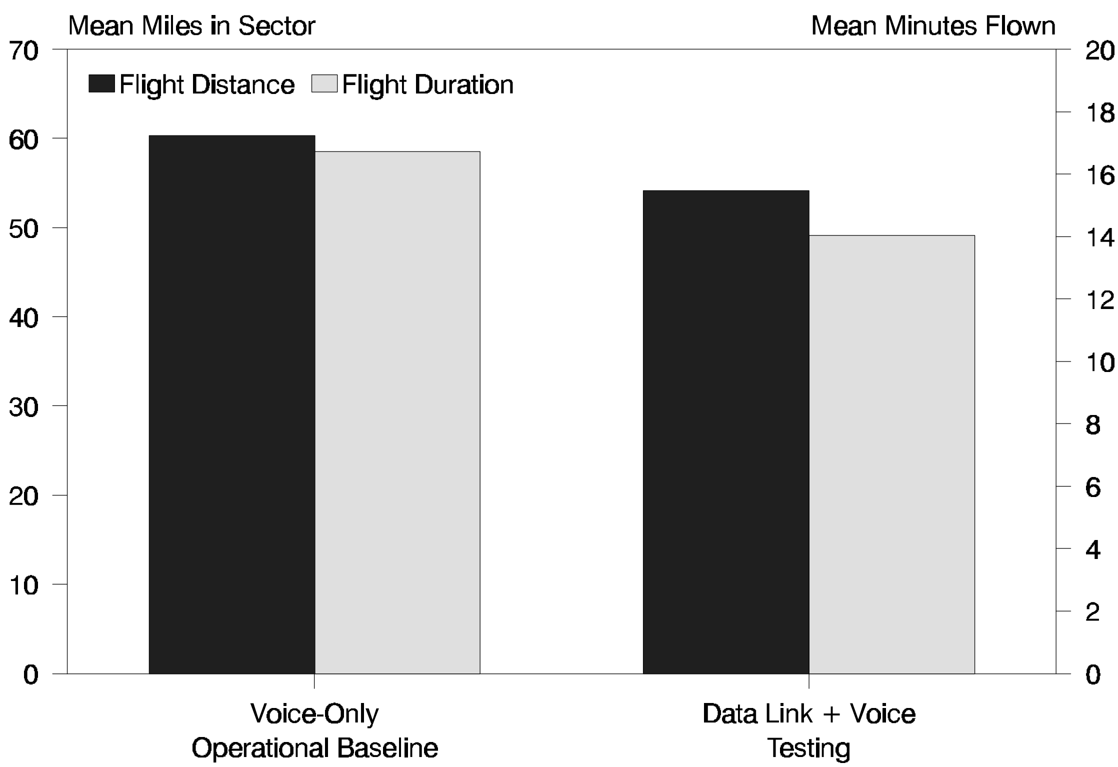

FIGURE 8. TIME AND DISTANCE FLOWN WITHIN SECTOR IN EXPERIMENT 1

both the historical baseline day and during testing were included in this calculation.

As shown in figure 9, each of the Data Link test runs yielded a mean per-aircraft arrival delay savings over the voice-only baseline day. For the nine Data Link test runs, mean savings ranged from slightly more than 1 minute to approximately 5 minutes. The mean arrival delay reduction across test runs was 2.83 minutes per aircraft.

5.1.2.4 Sector Throughput and System Productivity.

Improvements in flight efficiency and delay reductions that accrued to NAS users under Data Link testing were also reflected in measures of the productivity and effective capacity of the ATC system. The number of aircraft controlled by the Newark feeder and final controllers were tabulated for the 50-minute historical baseline period and for the nine Data Link test runs. As shown in figure 10, the controllers using Data Link admitted significantly more aircraft to the airspace than their counterparts during the matched time periods ($t_8=3.59$, $p<.001$). Of the total number of aircraft handled, the number of aircraft that landed at Newark during the 50-minute test period was also significantly higher with Data Link ($t_8=10.73$, $p<.001$).

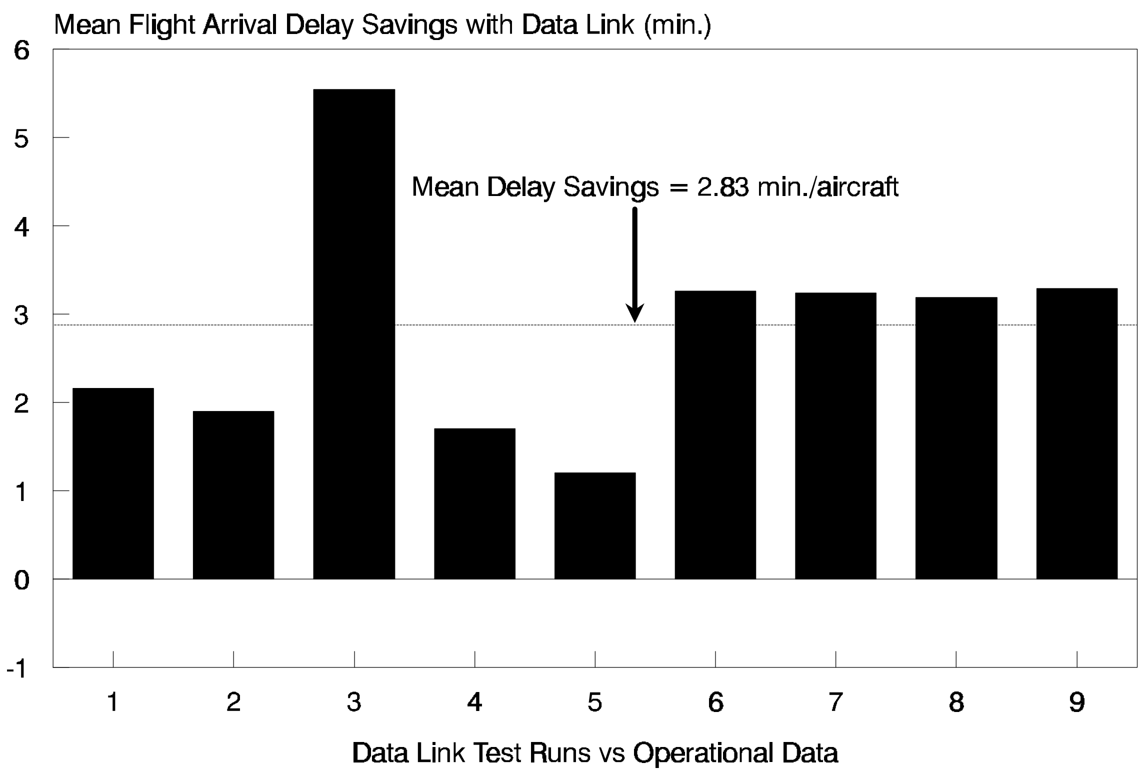

FIGURE 9. ARRIVAL DELAY SAVINGS IN EXPERIMENT 1

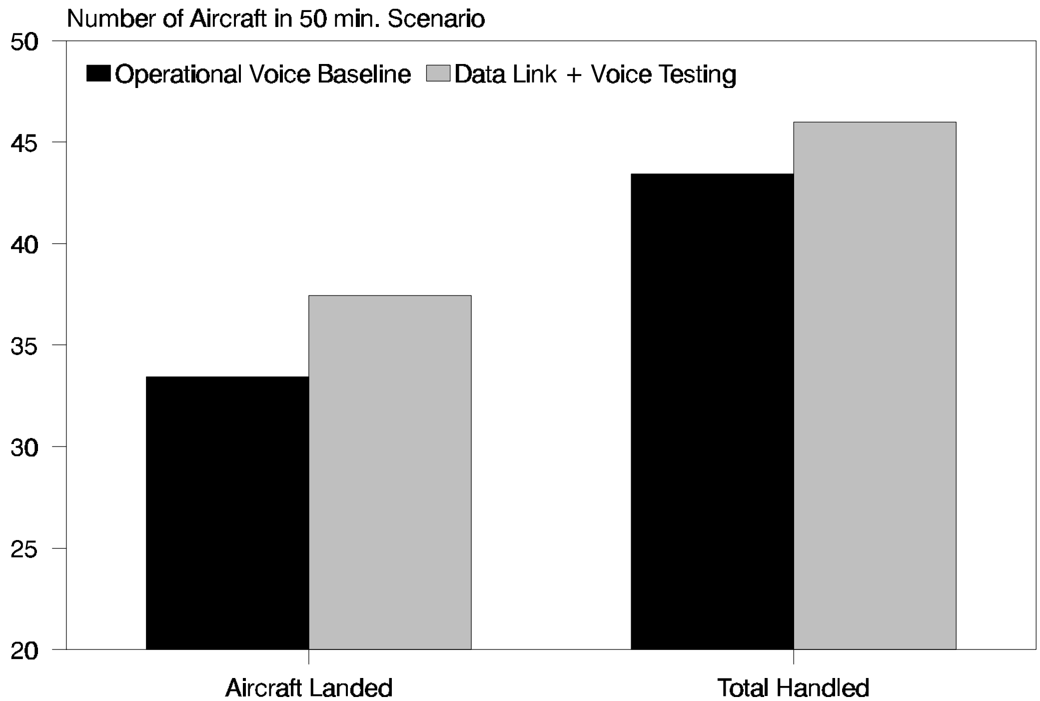

FIGURE 10. AIRCRAFT HANDLED AND LANDED IN EXPERIMENT 1

Interpreted as hourly measures of airspace capacity, these findings translate to an average increase of 6.18 more aircraft handled per hour with Data Link. When similarly adjusted to an hourly rate, 4.8 more aircraft were landed per hour with Data Link in comparison to the historical baseline day in which only voice radio communications were available.

5.1.3 Supervisory Performance Evaluation.

In order to determine whether the delay savings benefits identified during testing were achieved at any expense to the general quality of task performance exhibited by controllers, the observing supervisors were asked to judge the ATC operation during each test run. These judgments were made for eight factors potentially indicative of degraded sector performance. A five-point rating scale ranging from 1 “never occurred” to 5 “occurred unacceptably often” was used to quantify the judgments.

Mean ratings for each of the eight performance events are shown in figure 11. The supervisors indicated that a majority of the events either never occurred or occurred rarely during Data Link testing. The data indicate that omissions of flight progress strip marking tasks were more common than the other seven events. However, the mean rate of occurrence for this event remained “within normal limits.”

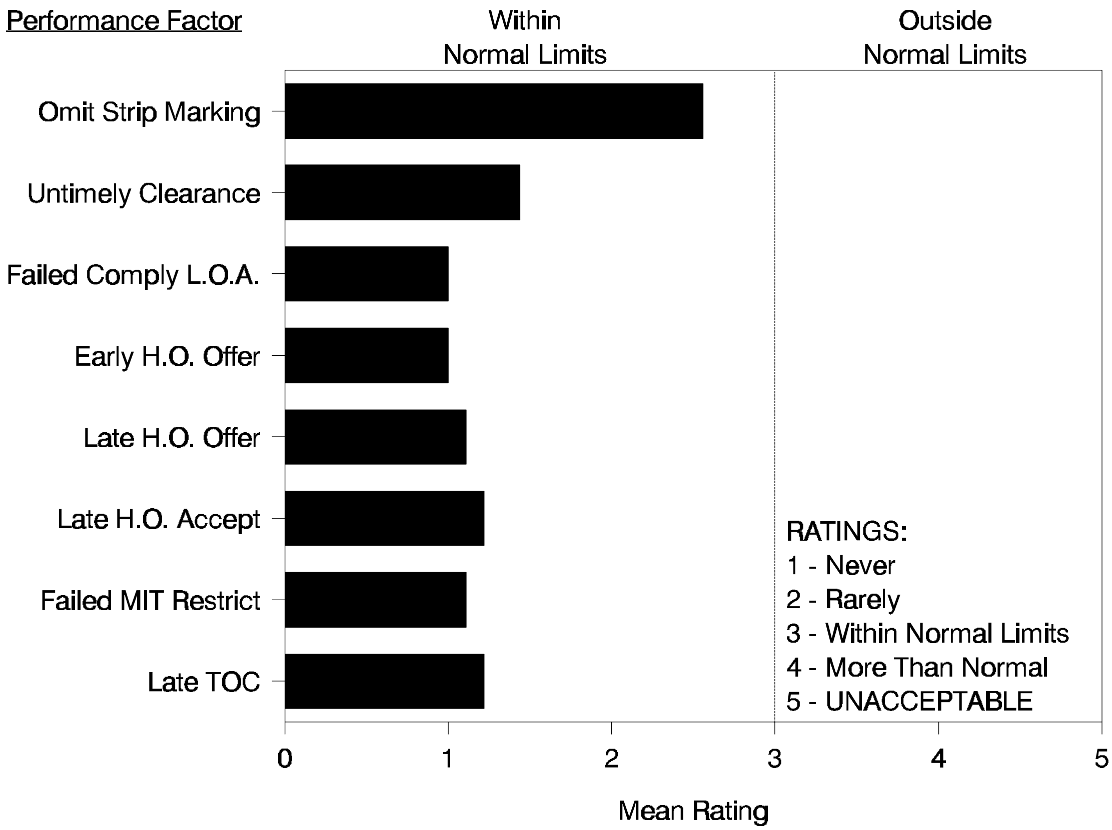

FIGURE 11. SECTOR PERFORMANCE RATINGS IN EXPERIMENT 1

5.1.4 Controller Workload.

Controller workload was assessed in experiment 1 using a binary judgment of workload acceptability and a relative rating of the workload that was experienced in comparison to normal workload at the position for a comparable traffic period. Using the binary measure, all of the 18 feeder and final position ratings obtained over the 9 test runs indicated that controller workload was "acceptable" and did not affect the controller's ability to control traffic safely and effectively.

The comparative workload ratings received from the feeder and final controllers are summarized in figure 12. As shown in the histograms, none of the controllers staffing the feeder or final positions indicated that their workload was "somewhat higher" or "much higher" than normal for their position. Five of the feeder controllers indicated that their workload was "much lower" than normal under voice-only communications at the operational position, while four indicated that it was "about the same." At the final position, four controllers indicated that their workload had been "much lower" or "somewhat lower" than normal under Data Link testing, while five rated the workload as "about the same."

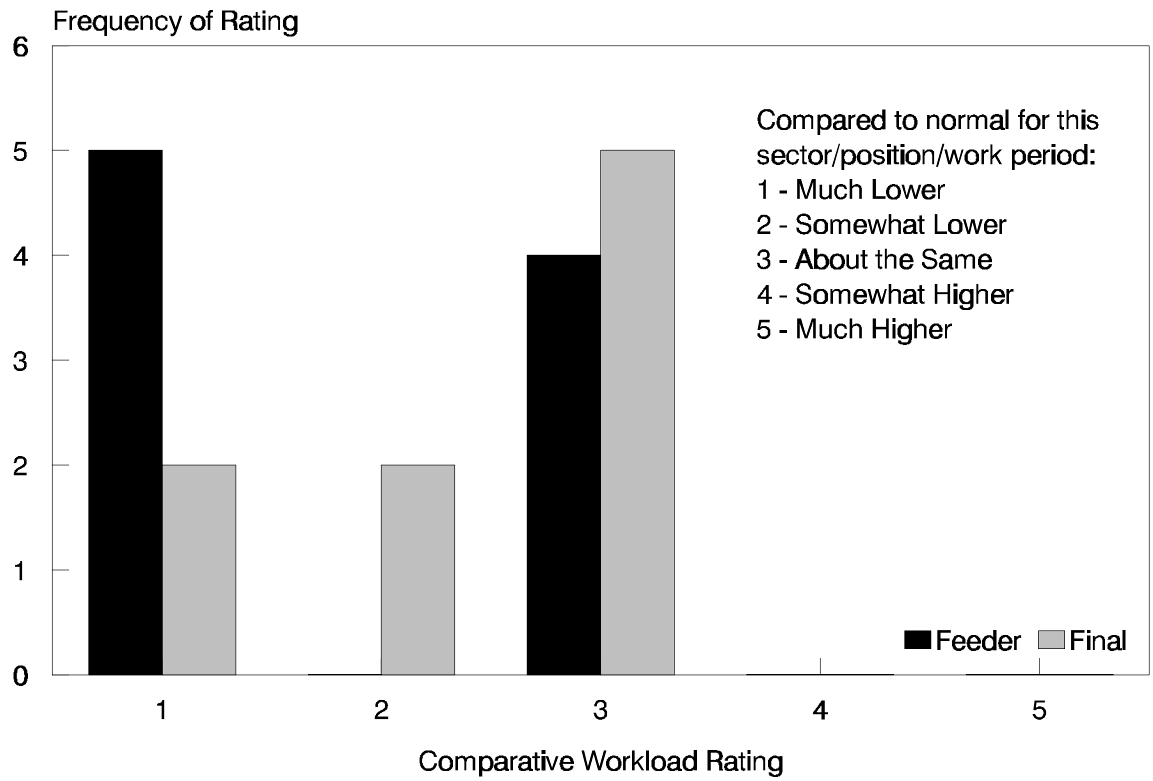

FIGURE 12. COMPARATIVE CONTROLLER WORKLOAD RATINGS IN EXPERIMENT 1

5.1.5 Communications.

Measures of communications activity and content that occurred during the historical baseline period and during Data Link testing were obtained as secondary outcome measures. It was expected that any benefits observed during testing would be associated with a redistribution of communications between the voice and Data Link channels.

5.1.5.1 Voice Radio Usage.

Figure 13 illustrates the reduction in voice radio usage that occurred during testing when Data Link communications were available. As shown in the figure, during the rush period on the baseline day at the New York TRACON, the radio channels were occupied by ATC communications for more than 53 minutes, and the feeder and final controllers sent nearly 500 voice messages to pilots. During Data Link testing, radio channel occupation time for the average test run dropped by 70 percent to approximately 16 minutes. The number of voice messages were reduced by 66 percent to 170.

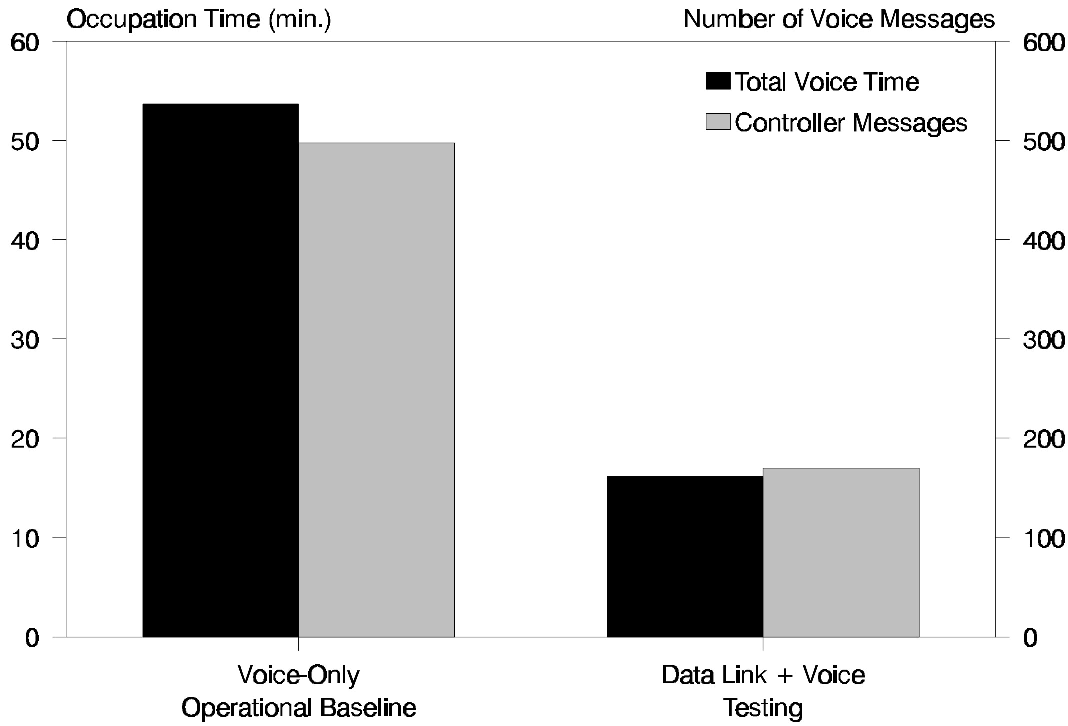

FIGURE 13. RADIO FREQUENCY OCCUPATION IN EXPERIMENT 1

5.1.5.2 Data Link and Voice Message Content.

Voice radio and Data Link messages sent by controllers were analyzed by grouping them into 22 mutually exclusive categories of clearances, requests, and informational transmissions to pilots. Definitions of the categories used in the content analysis of voice and Data Link transmissions made by controllers are given below.

Speed	A transmission that contained only a speed change.
Heading	A transmission that contained only a heading change with no reference to a fix or routing.
Altitude	A transmission that changed an aircraft's assigned altitude.
Comb.	
2 part	A transmission that contained 2 ATC instructions (e.g., speed and altitude).
3+part	A transmission that contained 3 or more ATC instructions.
TOC	A transmission that only transferred radio communication to the next controller.
TOC+	A transmission that transferred communication and sent additional information (e.g., reduce speed to 180kts. and contact tower on 119.3).
IC Resp.	A transmission that acknowledged an initial contact that may have contained terminal information.
IC Resp.+	A transmission that acknowledged initial contact and contained an ATC clearance.

Info.	A transmission that contained only general (or terminal) information (e.g., expect vectors across the final).
Route	A transmission that changed an aircraft heading or route and contained a fix or route name.
Correct.	A transmission that was made to correct, repeat or clarify a clearance, readback or initial contact.
Info. Req.	A transmission made to request information from the pilot (e.g., say airspeed).
Other	All transmissions made that do not fall within identified categories.
X Rstrn.	A transmission that included a restriction to cross a fix at a specific speed, heading, or altitude.
Approach	
Full	A transmission that contained the heading to intercept, all necessary altitude and speed restrictions, and a clearance to execute the approach.
Join	A transmission made to establish the aircraft on the final approach course (did not clear for approach).
Join+	A transmission made to establish the aircraft on the final approach course and contained a speed and/or altitude (did not clear for approach).
Partial	A transmission that contained the remainder of the approach clearance not given in Join or Join+.
Visuals	
Request	A request to report an airport or aircraft in sight.
Follow	A transmission that cleared an aircraft to follow another aircraft and execute a visual approach.
To Apt.	A transmission that cleared an aircraft to execute a visual approach to an in-sight airport.

Table 2 presents a breakdown of the voice messages transmitted on the historical baseline day, and of the average numbers of voice and Data Link messages sent during testing. When interpreting this table, it should be noted that comparison of the absolute numbers of messages sent in each category across conditions can be misleading since variable numbers of aircraft were handled by the controllers during the scenario periods.

Comparing voice messages on the baseline day and during testing, the table shows that the overall drop in radio frequency occupation with Data Link was attributable to reductions in a broad range of message types. Under Data Link, voice was used less frequently for all types of clearances, transfer of communications, and responses to initial contact calls.

Examining the distribution of messages between voice and Data Link during testing, the data show that Data Link was used for a clear majority of transfers of communications, initial contact responses, and altitude clearances. The two communications channels were shared fairly evenly for speeds, headings, and combination clearances. The data also show that Data Link was used for approach clearances. Furthermore, when a full clearance was not given in a single transmission, voice was typically used

TABLE 2. VOICE AND DATA LINK MESSAGE CONTENT IN EXPERIMENT 1

Message Type	Base Day Voice	Data Link Testing Avg. Voice	Data Link Testing Avg. Data Link
Speed	39	22	22
Heading	120	31	45
Altitude	69	21	40
Comb. 2 Part	52	18	13
Comb. 3+ Part	0	0	1
TOC	19	13	44
TOC+	34	6	0
IC Resp.	17	1	14
IC Resp.+	20	4	35
Info.	13	1	0
Route	0	0	0
Correct.	14	6	0
Info. Req.	15	2	0
Other	12	4	4
X Restrn.	0	0	1
Approach Full	1	4	8
Approach Join	33	19	2
Approach Join+	6	3	9
Appch. Partial	33	13	16
Visuals Request	0	1	0
Visuals Follow	0	1	0
Visuals To Apt.	0	0	0
TOTALS	497	170	253

to establish the aircraft on the final approach course. However, Data Link often was used to send the final clearance to execute.

A final noteworthy finding shown in table 2 is that, with Data Link, messages required because of inaccurate communications or uncertainties were reduced. These included messages to correct, repeat, or clarify a clearance, and messages requesting information from the pilot (e.g., “say airspeed,” “are you on frequency?”).

5.1.6 Summary of Experiment 1 Findings.

The results of this experiment showed that, when Data Link communications were available during testing, the Newark area controllers were able to avoid the use of flight holding that had occurred on the operational baseline day using only the voice radio system. In addition, mean flight distances and times within the terminal airspace were reduced, and earlier mean arrival times at EWR were achieved with Data Link. The productivity of the sector also was improved as both the number of flights handled and the number of aircraft landed increased with Data Link.

Beyond these NAS user and system benefits, controller workload during Data Link testing was either reduced or remained at a level equivalent to that normally experienced in the Newark area jet arrival positions during a traffic rush period. Operational assessments made by controllers and supervisors likewise suggested that the margin of safety under Data Link testing was either increased (41 percent of ratings), or was approximately the same as normal (59 percent of ratings) for this busy terminal area.

5.2 EXPERIMENT 2 -- COMPARISON OF DATA LINK AND VOICE-ONLY TESTING FOR EWR JET ARRIVAL WITH ADDED TRAFFIC.

Experiment 2 was conducted to assess the impact of Data Link when additional traffic was added to the Newark area jet arrival flow. As in experiment 1, this 57-minute test scenario was derived from an historical baseline day. However, 10 aircraft were added to the original 55 flight scenario to increase the demand on ATC resources. The additional aircraft consisted of actual flights that were scheduled to arrive during the selected rush period, but had been delayed for various reasons on the historical baseline day. The primary benefit hypothesized for this experiment was an improved ability to maintain arrival traffic flow during Data Link test runs when these were compared with equivalent test runs conducted under voice-only communications.

5.2.1 Operational Safety Assessments.

5.2.1.1 Aircraft Separation.

Of the nine voice-only and nine Data Link plus voice test runs completed for this experiment, an unsafe event was detected by the observing supervisor during one voice-only run. This event involved two aircraft that were on the final approach course. The event was corroborated by inspection of data obtained from the CDR tape. In accordance with the methodology adopted for this study, the flight performance and subjective data for the test run were eliminated from further consideration during analysis. The data from the matched Data Link test run in which the same controller participants staffed the feeder and final positions were also eliminated from subsequent benefit analyses.

5.2.1.2 Supervisor and Controller Ratings.

Expert operational assessments of safety for the 16 valid test runs are shown in figure 14. Mean margin of safety ratings for the feeder and final controllers as well as the observing supervisor were calculated by assigning values of 1 to 4 to ratings ranging from "unsafe" to "higher margin of safety than normal."

As shown in the figure, the mean ratings suggest that the margin of safety was increased when Data Link communications were available. None of the controllers or supervisors rated any of the Data Link or voice-only runs as "unsafe." Four of the Data Link runs were rated by the supervisors as having a greater margin of safety than normal, while four were rated as having a normal margin of safety. In comparison, none of the voice-only runs were rated as having a greater margin of safety than normal, seven as having a normal margin of safety, and one as having a lower margin of safety than normal.

Of the 16 ratings made by the feeder and final controllers under Data Link testing, six indicated that the margin of safety was higher than normal, while 10 indicated that the margin of safety was normal for the sector

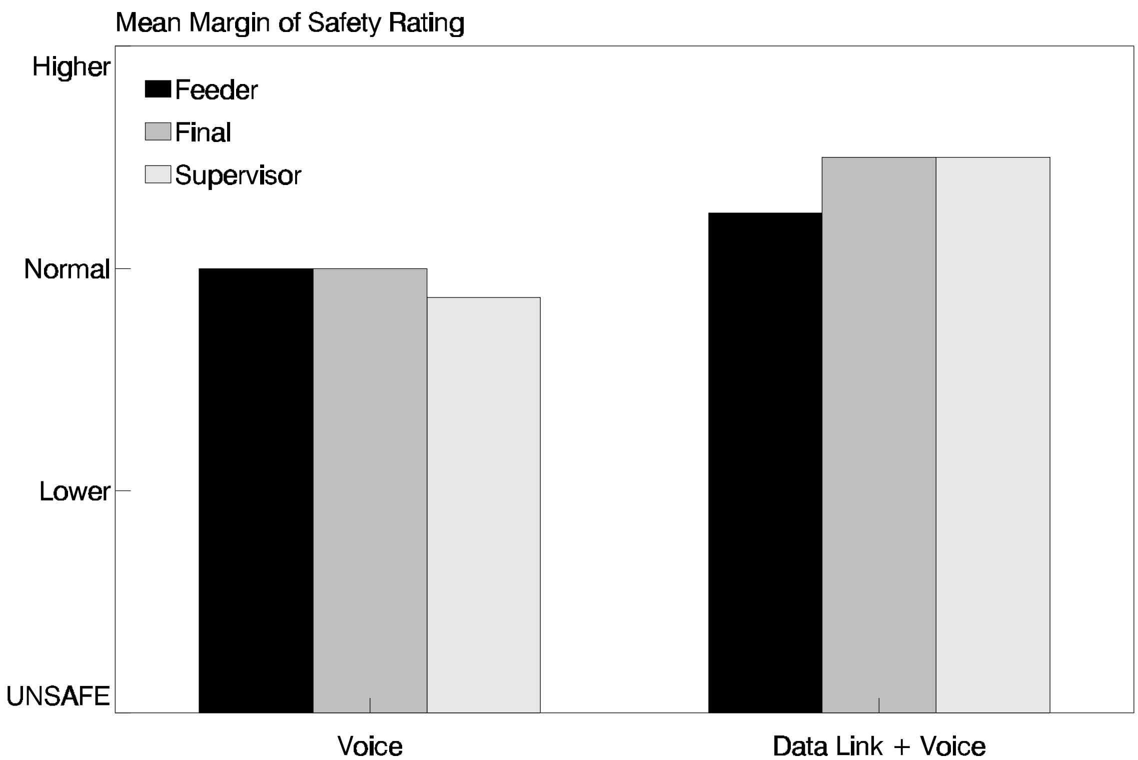

FIGURE 14. SUPERVISOR AND CONTROLLER SAFETY RATINGS IN EXPERIMENT 2

during a similar traffic rush period in the operational environment. For voice-only testing, all 16 ratings indicated that the margin of safety was normal.

5.2.2 Flight Efficiency and Airspace Productivity.

The following subsections present objective data from the eight pairs of voice-only and Data Link test runs. These data describe changes in flight arrival delays and operational efficiency that were associated with the use of Data Link to supplement the voice radio communications channel at the feeder and final positions.

5.2.2.1 Sector Entry Time.

As in experiment 1, sector entry time was used as a measure in this experiment to capture any effect of Data Link communications on the controllers' ability to maintain traffic flow into the terminal area by minimizing or avoiding the use of additional restrictions and/or holding in en route airspace. Sector entry delay savings or losses for each flight in a Data Link test run were calculated by subtracting the time at which the aircraft crossed the sector boundary from its boundary crossing time on a matched voice baseline test run. Paired test runs were those in which the same controller participants staffed the feeder and final positions. As described in section 4.6, in order to control for learning effects, the Data Link and voice runs used different variations of the test scenario. Approximately one-half of the participants experienced the Data Link run first, while the other one-half experienced the voice-only test run first. Only those aircraft which entered the sector during both paired runs were included in this calculation.

As shown in figure 15, six of the eight Data Link test runs yielded a mean per-aircraft delay savings over the matched voice-only baselines. The average Data Link time savings for these runs ranged from .2 minutes to 4.3 minutes per aircraft. In the remaining two comparisons, no difference between the voice-only and Data Link mean sector entry time was detected in one run, while for the other, the voice-only run produced mean sector entry delays that were 1.4 minutes shorter than those measured in the Data Link run. Averaged across all test runs, the mean per-aircraft sector entry time was 1.36 minutes earlier with Data Link than in the comparable voice-only communications runs.

The mean decrease in sector entry delay was attributable to differences in restrictions placed on arriving flights between the voice-only baseline and the Data Link test trials. Flight holding and MIT restrictions were used by the controllers in both the voice-only and Data Link runs in order to

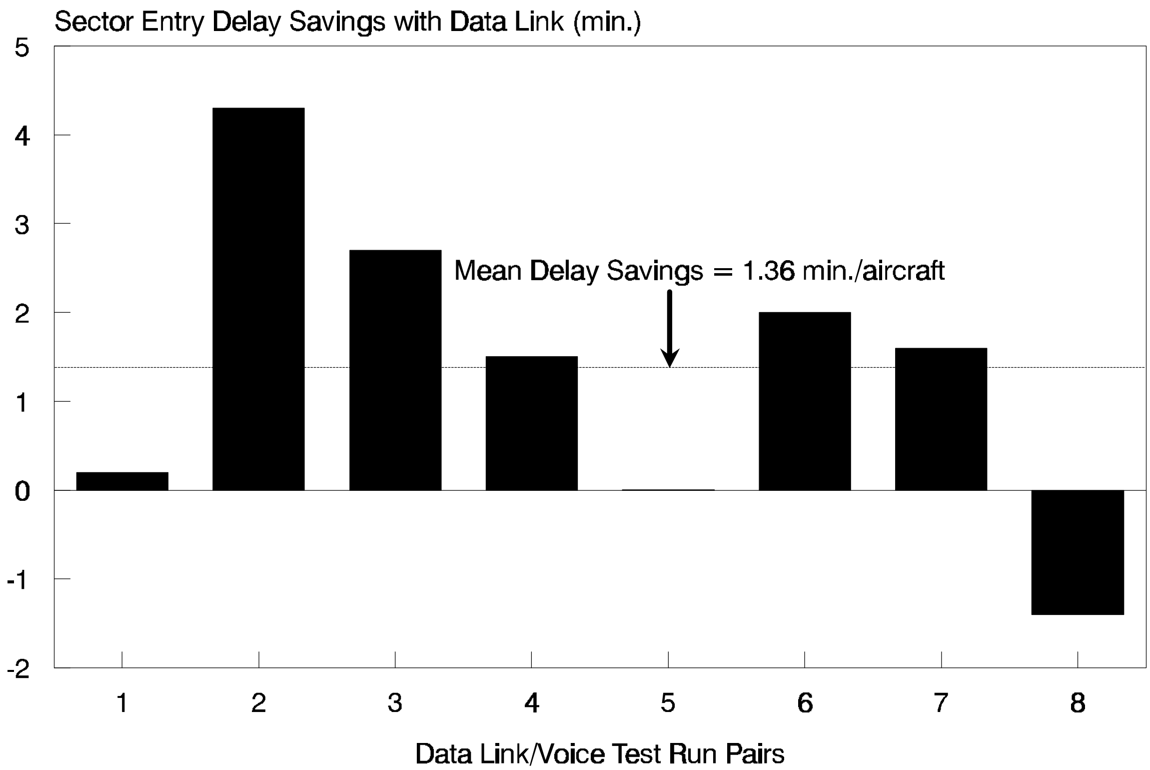

FIGURE 15. SECTOR ENTRY DELAY SAVINGS IN EXPERIMENT 2

effectively control the increased traffic volume presented by the test scenario of experiment 2. However, in six of the eight run comparisons, the time at which the holding actions and restrictions were imposed was either postponed or the duration of the holding and restriction periods were reduced when Data Link communications were available. This resulted in an average reduction in en route flight time and distance for the affected flights, and a subsequent earlier entry to the Newark area terminal airspace. The mean sector entry delay savings achieved with Data Link in experiment 2 were approximately .6 minutes smaller than those recorded for experiment 1. However, it should be noted that the traffic load was approximately 35 percent higher in experiment 2 than experiment 1.

5.2.2.2 Time and Distance Flown in Sector.

As in experiment 1, once the aircraft were admitted to the sector, measures of the time and distance flown within the feeder/final airspace were used to assess any effect of the expanded air-ground communications channel on the ability of controllers to efficiently space and merge arriving aircraft as they maneuvered to the landing runway.

Figure 16 presents the mean flight distance and time for the Newark jet arrivals that landed during the 57-minute scenario under voice-only baseline and Data Link testing. As shown in the figure, the average arrival during voice-only testing flew approximately 54 miles within the feeder/final airspace over a period of approximately 14.5 minutes. During Data Link testing, the mean flight distance for an aircraft dropped to approximately 52 miles, while flight time was reduced to approximately 13.8 minutes, for an average per-aircraft savings of 1.7 miles and .7 minutes. Formal comparisons of the baseline and Data Link test data indicated that the reduction in flight time was statistically significant ($t_7=2.02$, $p=.04$).

5.2.2.3 Flight Arrival Delay.

For those flights that were completed within the 57-minute scenario time, arrival delay savings or losses for each flight in a Data Link test run were calculated by subtracting the time at which the aircraft crossed the problem exit point for the landing runway from its crossing time during the matched voice-only test run. Only those aircraft that entered the sector and landed during both of the matched voice baseline and Data Link runs were included in this calculation.

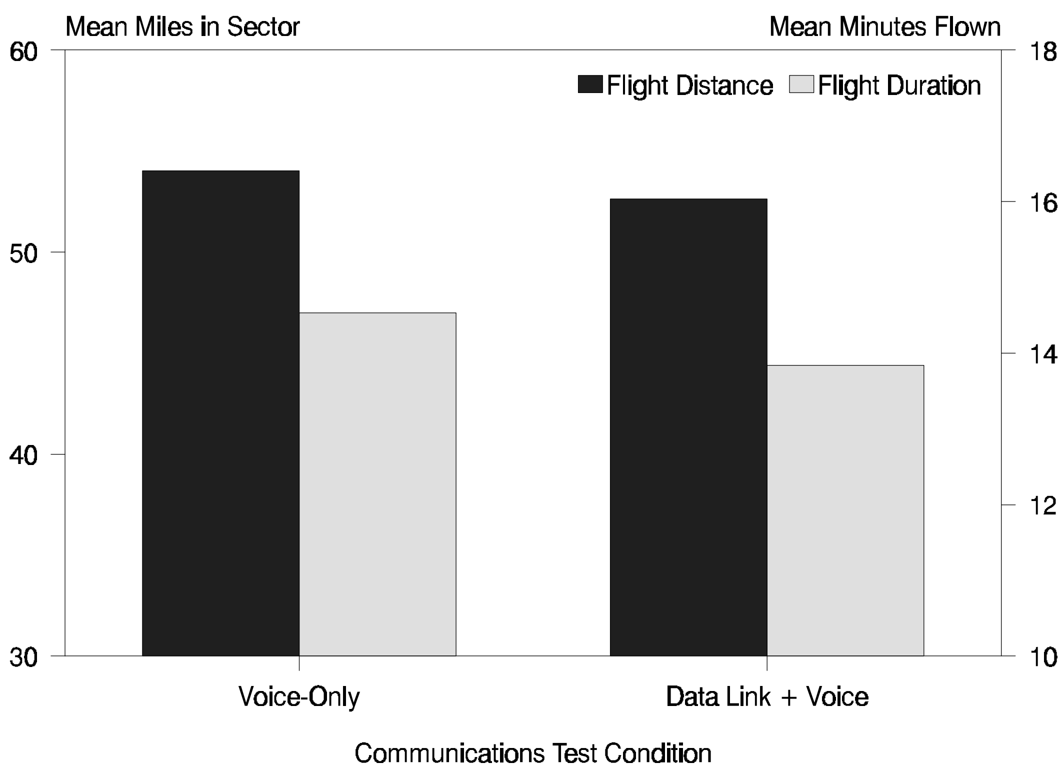

FIGURE 16. TIME AND DISTANCE FLOWN WITHIN SECTOR IN EXPERIMENT 2

As shown in figure 17, overall arrival delay savings were achieved with Data Link in six of the eight test run comparisons. These savings ranged from 1 minute to 4.2 minutes per aircraft. In the remaining two comparisons, the voice-only runs showed an advantage over the Data Link runs of .2 and 2 minutes per aircraft. Computed over all eight run comparisons, Data Link yielded an average delay reduction of 1.39 minutes per aircraft.

5.2.2.4 Airspace Productivity.

Measures of productivity and effective capacity of the ATC system under voice-only and Data Link testing were calculated by examining the number of aircraft handled and landed during the 57-minute test runs. As shown in figure 18, the controllers using Data Link admitted more aircraft to the airspace than they did during the matched voice-only runs. The size of the increase with Data Link was small, but was reliable over the comparisons and yielded a statistically significant difference ($t_7=2.05$, $p=.04$). Of the total number of aircraft handled, an average of 45 landed at Newark during the 57-minute test period with Data Link, while under voice-only conditions an average of 42.25 reached the airport. This improvement with Data Link was also statistically significant ($t_7=2.06$, $p=.04$).

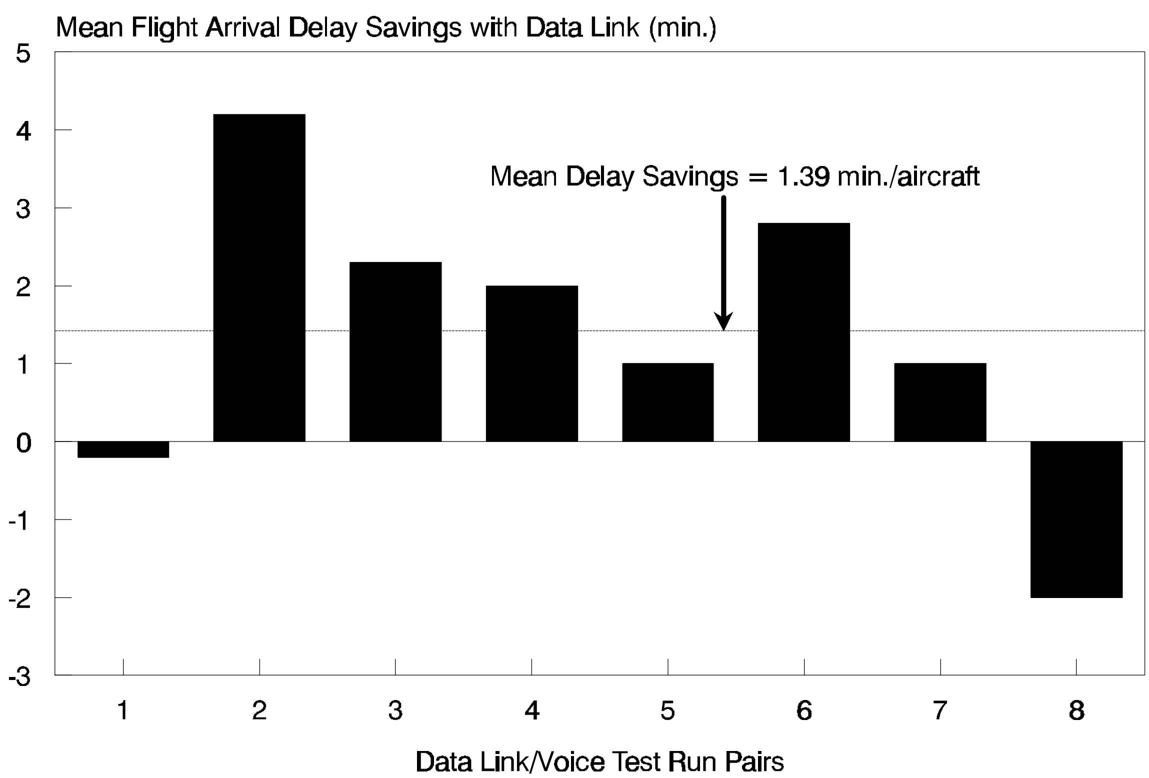

FIGURE 17. ARRIVAL DELAY SAVINGS IN EXPERIMENT 2

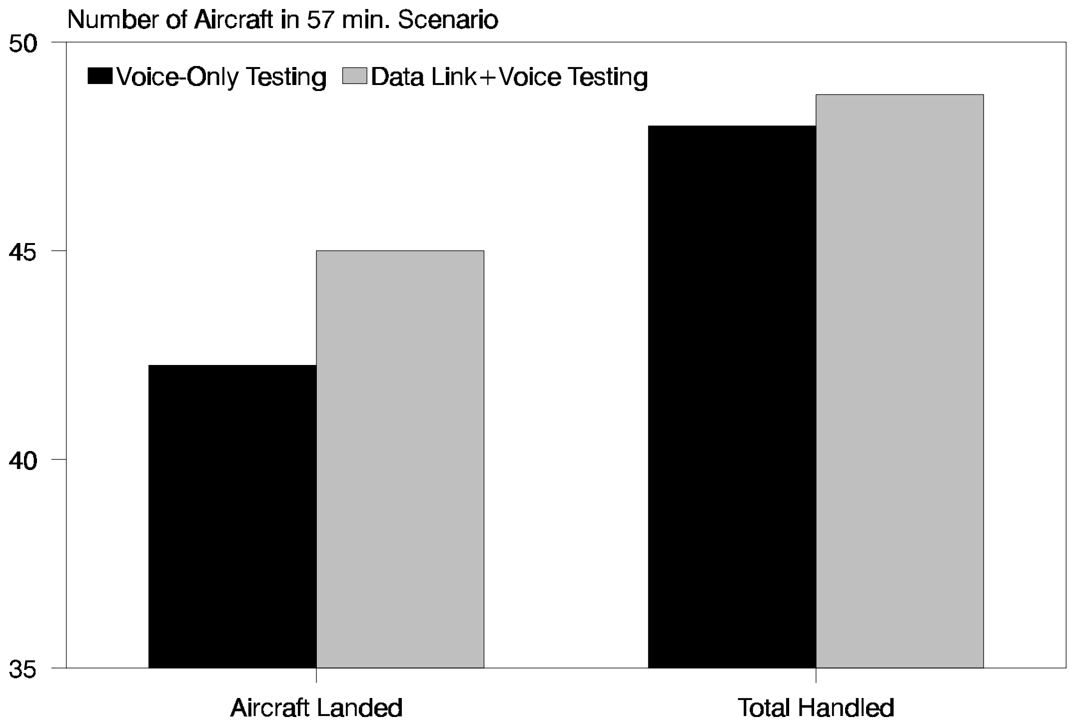

FIGURE 18. AIRCRAFT HANDLED AND LANDED IN EXPERIMENT 2

Interpreted as hourly measures of airspace capacity, these findings translate to an average increase of .79 more aircraft handled per hour, and 2.89 more aircraft landed per hour with Data Link in comparison to the test runs in which only voice radio communications were available.

5.2.3 Supervisory Performance Evaluation.

In order to determine whether the delay savings benefits identified during testing were achieved at any expense to the general quality of task performance exhibited by controllers, the observing supervisors evaluated the ATC operation during each test run on eight factors potentially indicative of degraded sector performance. A five-point rating scale ranging from 1 “never occurred” to 5 “occurred unacceptably often” was used to quantify the judgments.

Mean ratings for each of the eight performance events are shown in figure 19. The supervisors indicated that a majority of the events either never occurred or occurred rarely during voice-only and Data Link testing. The data suggest that omissions of flight progress strip marking tasks and sending clearances earlier or later than appropriate were more common than the other six events in both the Data Link and voice runs. In addition, for these two events, the rate of occurrence appeared to have been higher

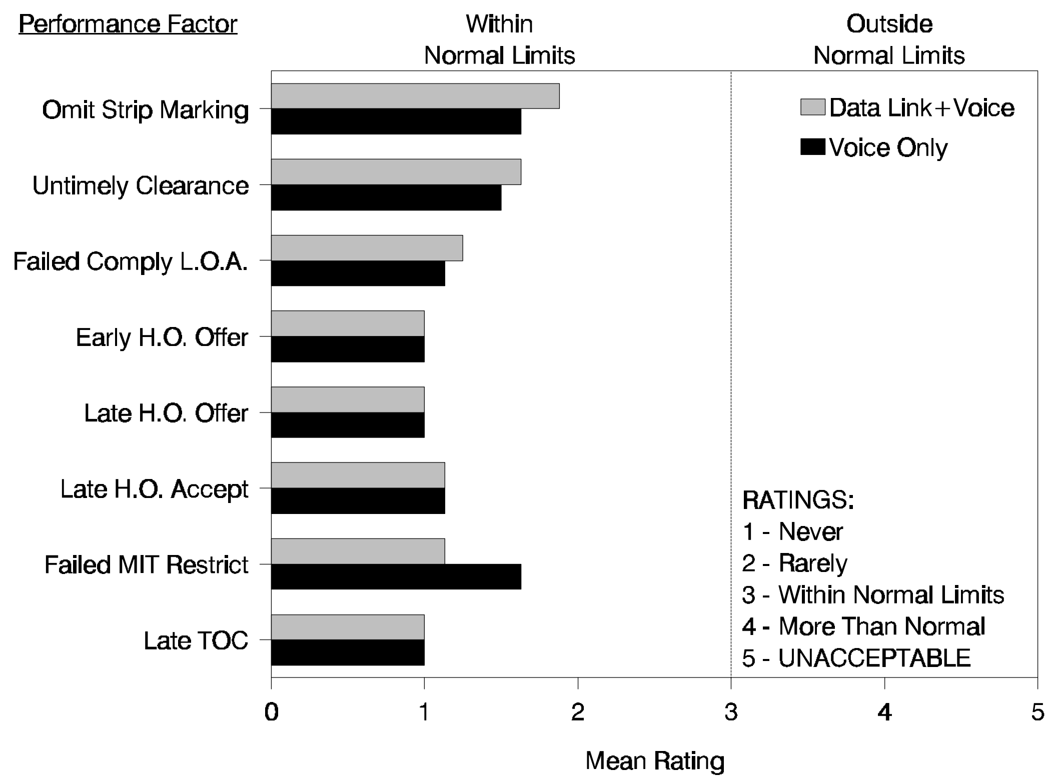

FIGURE 19. SECTOR PERFORMANCE RATINGS IN EXPERIMENT 2

during the Data Link runs. However, the mean rates of occurrence for both factors were "within normal limits."

The data also indicate that failures to meet mile in trail restrictions were more common in the voice test runs than in the Data Link runs. However, the mean rate of occurrence was also "within normal limits."

5.2.4 Controller Workload.

Controller workload was assessed in experiment 2 using three techniques. As in experiment 1, controllers made a binary judgment of workload acceptability and a relative rating of the workload that was experienced in comparison to a their normal workload at the position for a comparable traffic period. In addition, because the experiment involved direct comparison of voice-only and Data Link test runs using the same experimental subjects, the controllers also made an absolute rating of each run using a standardized workload rating technique (SWAT).

All of the 32 feeder and final position ratings obtained over the 16 voice-only and Data Link test runs indicated that controller workload was “acceptable” and did not affect the controller’s ability to control traffic safely and effectively.

The comparative workload ratings received from the feeder and final controllers are summarized in figures 20 and 21. As shown in the histograms, none of the controllers staffing the feeder or final positions indicated that their workload was “much higher” than normal for their position under either communications condition. One of the feeder controllers and three of the final controllers felt that their workload had been “somewhat higher than normal” under voice-only testing. None of the feeder controllers and two of the final controllers assigned this rating to the Data Link runs.

Five of the feeder controllers and four of the final controllers indicated that their workload had been “much lower” or “somewhat lower” than normal for their position during Data Link runs. Conversely, only one feeder controller and none of the final controllers assigned either of these ratings to the voice-only test runs.

The results obtained with SWAT corroborated and quantified the findings obtained with the comparative ratings. As shown in figure 22, the mean SWAT workload scores for the feeder position were lower than those for

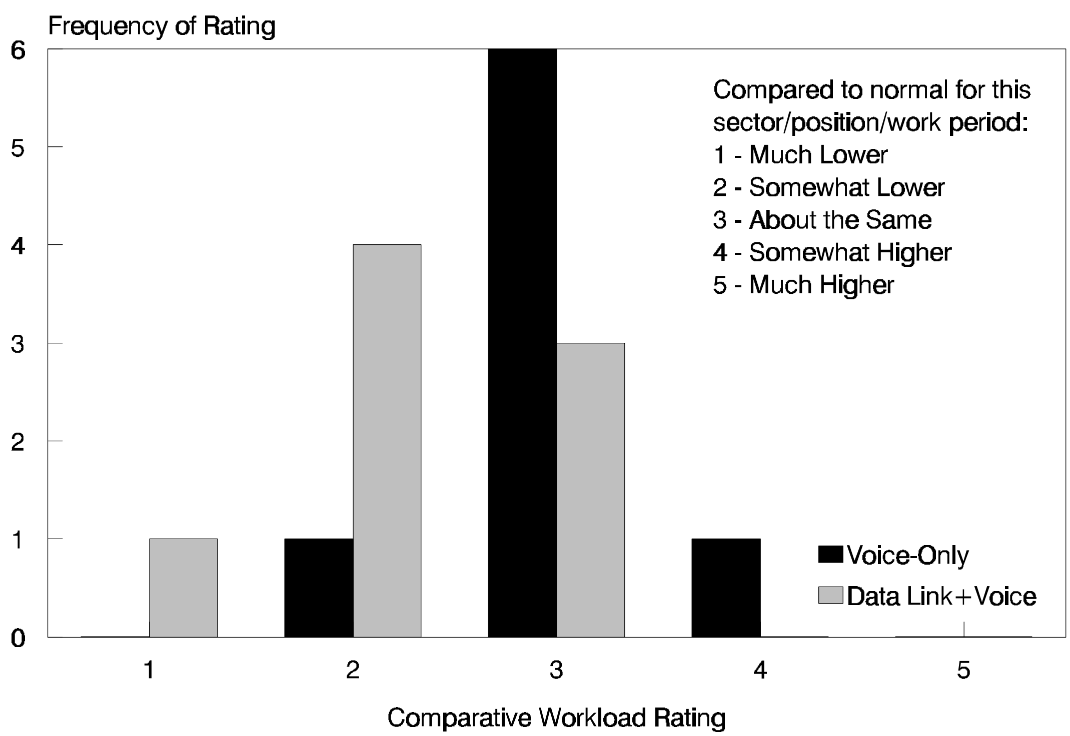

FIGURE 20. COMPARATIVE FEEDER CONTROLLER WORKLOAD RATINGS IN EXPERIMENT 2

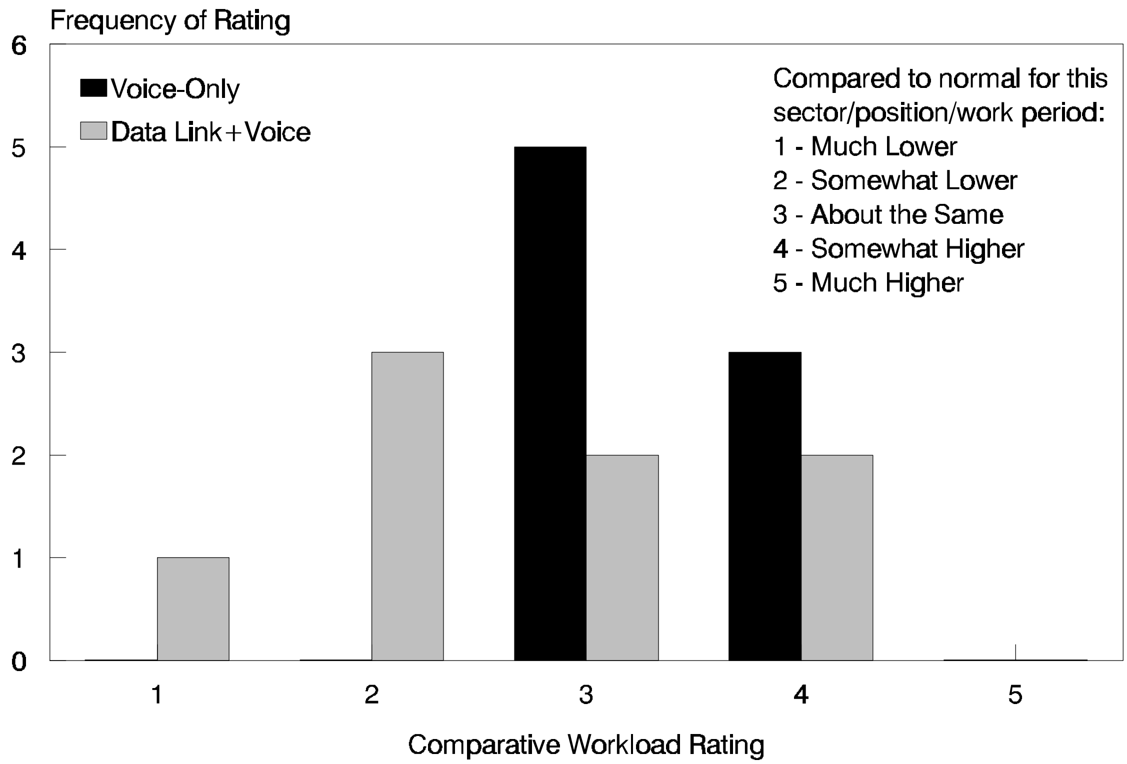

FIGURE 21. COMPARATIVE FINAL CONTROLLER WORKLOAD RATINGS IN EXPERIMENT 2

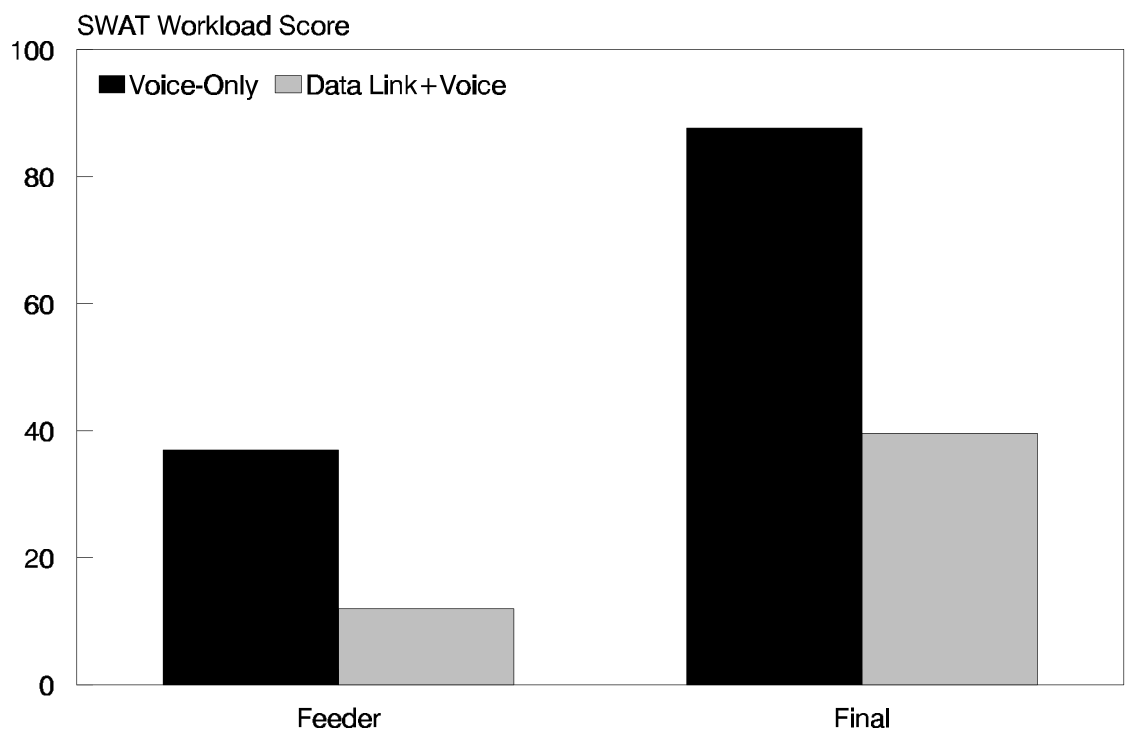

FIGURE 22. SWAT WORKLOAD SCORES IN EXPERIMENT 2

the final position under both voice-only and Data Link testing. At both positions, however, SWAT workload scores were significantly lower when using Data Link than when using only the voice radio communications system (feeder: $t_7=2.27$, $p=.03$; final: $t_7=5.11$, $p<.001$).

5.2.5 Communications.

5.2.5.1 Voice Radio Usage.

Figure 23 illustrates the reduction in voice radio usage that occurred during testing when Data Link communications were available. As shown in the figure, during voice-only testing, the radio channels were occupied by ATC communications for an average of more than 54 minutes, and the feeder and final controllers sent an average of 510 voice messages to pilots. During Data Link testing, radio channel occupation time for the average test run dropped by 61 percent to approximately 21 minutes. The number of voice messages were reduced by 45 percent to 280.

5.2.5.2 Data Link and Voice Message Content.

Voice radio and Data Link messages sent by controllers were analyzed by grouping them into 22 mutually exclusive categories of clearances,

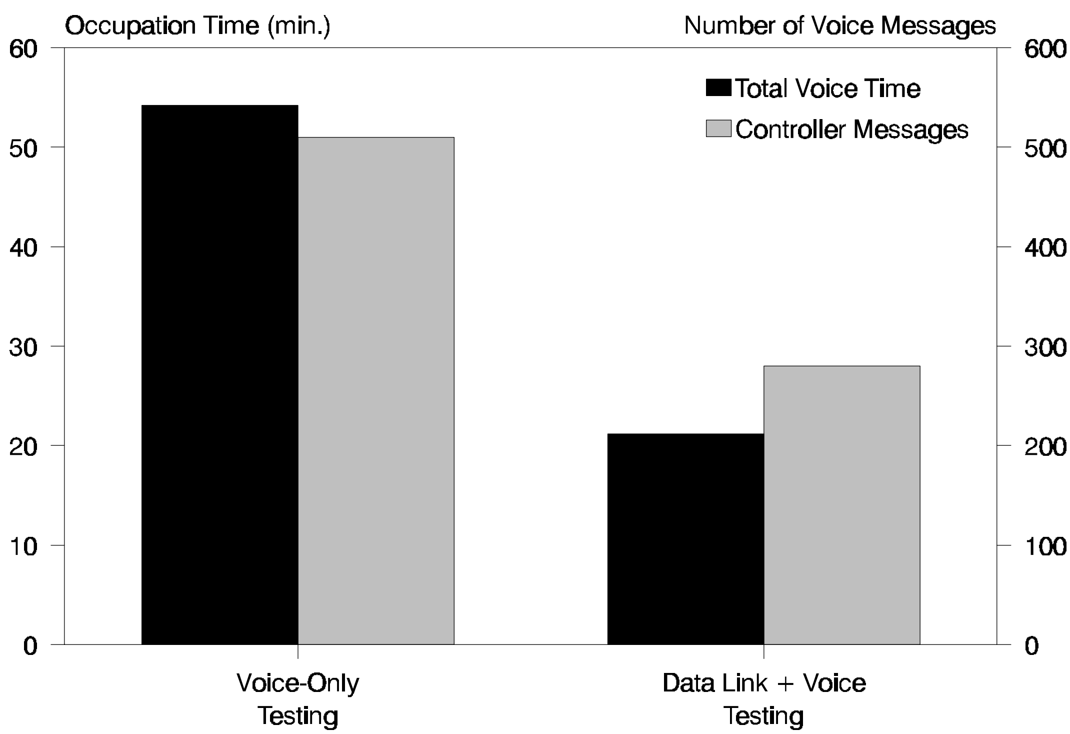

FIGURE 23. RADIO FREQUENCY OCCUPATION IN EXPERIMENT 1

requests, and informational transmissions to pilots. Definitions of the categories used in the content analysis of voice and Data Link transmissions made by controllers are presented in section 5.1.5.2.

Table 3 presents a breakdown of the average number of voice messages transmitted during voice-only testing and the average numbers of voice and Data Link messages sent during Data Link testing. When interpreting this table, it should be noted that comparison of the absolute numbers of messages sent in each category across conditions can be misleading since variable numbers of aircraft were handled by the controllers during the scenario period.

TABLE 3. VOICE AND DATA LINK MESSAGE CONTENT IN EXPERIMENT 2

Message Type	Voice-Only Testing Avg.	Data Link Testing Avg.	
	Voice	Voice	Data Link
Speed	42	26	23
Heading	120	67	61
Altitude	74	36	44
Comb. 2 Part	44	31	12
Comb. 3+ Part	0	0	1
TOC	41	20	48
TOC+	25	9	0
IC Resp.	12	5	21
IC Resp.+	43	11	42
Info.	5	6	0
Route	0	0	0
Correct.	11	8	0
Info. Req.	4	3	0
Other	4	2	0
X Restrn.	0	0	1
Approach Full	7	6	7
Approach Join	33	24	1
Approach Join+	9	3	7
Appch. Partial	33	16	21
Visuals Request	1	2	0
Visuals Follow	2	5	0
Visuals To Apt.	1	1	0
TOTALS	510	280	292

Comparing voice messages alone, the table shows that the overall drop in radio frequency occupation with Data Link was attributable to reductions in a broad range of message types. With Data Link, voice was used less frequently for all types of clearances (including approach), transfer of communications, and responses to initial contact calls.

Examining the distribution of messages between voice and Data Link during testing, the data show that Data Link was used for a clear majority of transfers of communications and initial contact responses. Combination clearances were sent more often via voice. The two communications channels were shared fairly evenly for single speed, heading, and altitude clearances. As in experiment 1, the data also show that Data Link was used for approach clearances. Furthermore, when a full clearance was not given in a single transmission, voice was typically used to establish the aircraft on the final approach course. However, Data Link often was used to send the final clearance to execute.

In agreement with the results of experiment 1, the data also show that, with Data Link, messages required because of inaccurate communications or uncertainties were reduced. These included messages to correct, repeat or clarify a clearance, and messages requesting information from the pilot (e.g., “say airspeed,” “are you on frequency?”).

5.2.6 Summary of Experiment 2 Findings.

This experiment compared voice-only test runs and Data Link test runs in a second jet arrival scenario with the level of traffic significantly increased over that tested in experiment 1. As in experiment 1, the results showed that, with Data Link, the Newark area controllers were able to handle more aircraft, reduce sector entry and arrival delays, and improve flight efficiency. Holding and additional restrictions were required to handle the increased volume in both voice-only and Data Link runs. However, these measures were used less frequently and for shorter periods with Data Link. The resulting improvements with Data Link were somewhat smaller than those observed in experiment 1, but they were achieved under traffic demands which were 35 percent greater.

Operational assessments made by controllers and supervisors indicated that the margin of safety under Data Link testing was increased in 41 percent of the ratings and was approximately the same as normal for this busy terminal area in 59 percent of ratings. Under voice-only testing, none of the runs were rated as having an improved margin of safety, and one was rated as having a lower margin of safety than normal. Finally, quantified assessments showed that controller workload was significantly lower for both the feeder and final controllers when using Data Link than when using voice radio alone.

5.3 EXPERIMENT 3 -- COMPARISON OF DATA LINK AND VOICE-ONLY TESTING FOR NEWARK AREA SATELLITE ARRIVAL.

Experiment 3 examined Data Link's impact on the satellite arrival problem. As discussed in section 4.1.2, the MUGZY airspace requires controllers to handle commuter arrivals to EWR, arrivals to Teterboro, and arrivals to several other satellite general aviation airports. The airspace is complex because of crossing traffic with varying aircraft types, operations under visual flight rules (VFR) and multiple destinations. However, during this test, traffic volume was not as high as that experienced in the Newark area jet arrival airspace.

This experiment was conducted to determine whether the addition of Data Link communications would improve service to both commuter and business/general aviation arrivals. In addition, as in the previous experiments, Data Link's impact on controller workload, performance, and the safety of ATC operations were assessed.

5.3.1 Operational Safety Assessments.

5.3.1.1 Aircraft Separation.

No aircraft separation violations were identified in any of the 18 voice-only and Data Link plus voice radio test runs.

5.3.1.2 Supervisor and Controller Ratings.

Expert operational assessments of safety for the 18 test runs are shown in figure 24. Mean margin of safety ratings for the radar and handoff controllers as well as the observing supervisor were calculated by assigning values of 1 to 4 to ratings ranging from "unsafe" to "higher margin of safety than normal."

None of the controllers or supervisors rated any of the Data Link or voice-only runs as "unsafe." Four of the Data Link runs were rated by the supervisors as having a greater margin of safety than normal, while four were rated as having a normal margin of safety. In comparison, none of the voice-only runs were rated as having a greater margin of safety than normal, and eight as having a normal margin of safety for the MUGZY position.

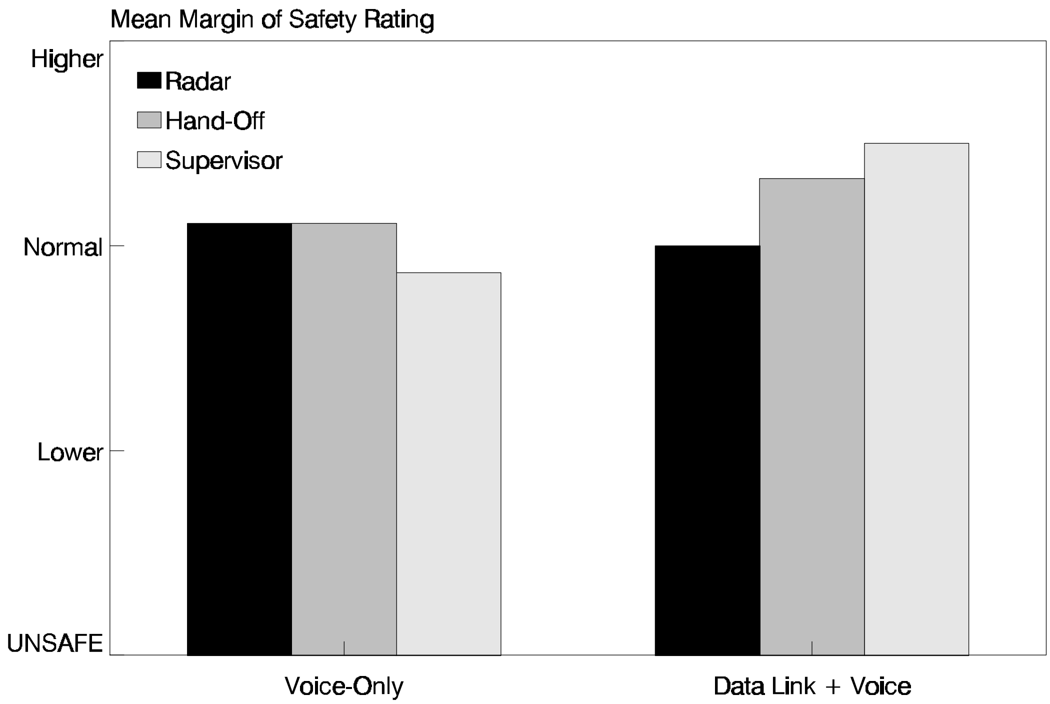

FIGURE 24. SUPERVISOR AND CONTROLLER SAFETY RATINGS IN EXPERIMENT 3

Of the 18 ratings made by the radar and handoff controllers under Data Link testing, 6 indicated that the margin of safety was higher than normal, while 9 indicated that the margin of safety was normal for the sector during a similar traffic rush period in the operational environment. Three ratings indicated that the margin of safety was lower than normal. None of the ratings indicated that the conditions had been unsafe.

For voice-only testing, 2 controller ratings suggested that the margin of safety was higher than normal, while the remaining 16 ratings indicated that the margin of safety was normal.

Written comments provided by the controllers who had assigned lower than normal margin of safety ratings to Data Link test runs indicated that these were attributable to inadequately developed procedures for sharing of communications tasks between the radar and handoff controllers. These comments suggested that the two controllers had not agreed upon policies for distribution of Data Link duties, and that either the handoff or radar controller was unsure of what actions had been initiated by the other. Conversely, comments received from the six controllers who had assigned a “higher than normal” margin of safety rating with Data Link indicated that these controllers were more comfortable with the test runs because they had devised mutually accepted strategies for sharing Data

Link tasking and coordination procedures to insure shared situation awareness. (See section 5.6 for further data on controller duties.)

5.3.2 Flight Efficiency and Airspace Productivity.

Analyses of the flight performance data revealed no reliable differences between the voice-only and Data Link test runs in the satellite arrival problem. Table 4. presents a summary of the results for the three primary airports served by the MUGZY position. All values in the table are means across the nine voice-only and Data Link comparisons.

TABLE 4. MEAN FLIGHT EFFICIENCY AND AIRSPACE PRODUCTIVITY RESULTS FOR SATELLITE ARRIVALS

EWR (Turboprop Commuters)	Voice Only	Data Link + Voice
Sector Entry Delay Savings (min.)		.16
Arrival Delay Savings (min.)	.68	
Time in Sector	6.93	7.01
Distance in Sector	28.36	28.55
Aircraft Handled (45 min.)	10.33	10.33
Aircraft Landed (45 min.)	8.44	8.22

TEB (Business GA)	Voice Only	Data Link + Voice
Sector Entry Delay Savings (min.)		.14
Arrival Delay Savings (min.)		.02
Time in Sector	7.05	6.71
Distance in Sector	29.71	28.30
Aircraft Handled (45 min.)	21	21.22
Aircraft Landed (45 min.)	18.33	18.33

MMU (GA)	Voice Only	Data Link + Voice
Sector Entry Delay Savings (min.)		.62
Arrival Delay Savings (min.)		.11
Time in Sector	3.52	3.84
Distance in Sector	14.95	14.75
Aircraft Handled (45 min.)	3.33	3.33
Aircraft Landed (45 min.)	3.22	3.33

As shown in the table, Data Link showed apparent advantages in mean sector entry delay for aircraft bound for all three airports, and in arrival delay for Teterboro (TEB) and Morristown (MMU). Likewise, both TEB and MMU arrivals had average times and distances flown within MUGZY which were slightly shorter when Data Link communications were available. However, none of these improvements were statistically significant ($p > .10$).

Airspace productivity measures also failed to reveal differences between the voice-only and Data Link runs. In both communications conditions, approximately 34 arriving aircraft were handled by the controllers and 30 arrived at their destination airports within the 45-minute scenarios.

No flight holding or MIT restrictions were requested by the controllers or supervisors to reduce traffic volume in any of the voice or Data Link test runs.

5.3.3 Supervisory Performance Evaluation.

As in experiments 1 and 2, the observing supervisors evaluated the ATC operation during each test run on eight factors potentially indicative of degraded sector performance. A five-point rating scale ranging from 1 "never occurred" to 5 "occurred unacceptably often" was used to quantify the judgments.

Mean ratings for each of the eight performance events are shown in figure 25. The supervisors indicated that a majority of the events either never occurred or occurred rarely during voice-only and Data Link testing. As in experiments 1 and 2, the data indicate that omissions of flight progress strip marking tasks were more common than the other eight events in both the Data Link and voice runs. In addition, issuing untimely clearances, failing to comply with letters of agreement, and failing to meet MIT restrictions appeared more common in voice-only than in Data Link runs. However, the mean rates of occurrence for all of these events were "within normal limits."

5.3.4 Controller Workload.

Controller workload was assessed in experiment 3 using three techniques. As in experiment 1, controllers made a binary judgment of workload acceptability, and a relative rating of the workload that was experienced in comparison to a their normal workload at the position for a comparable traffic period. In addition, because the experiment involved direct comparison of voice-only and Data Link test runs using the same

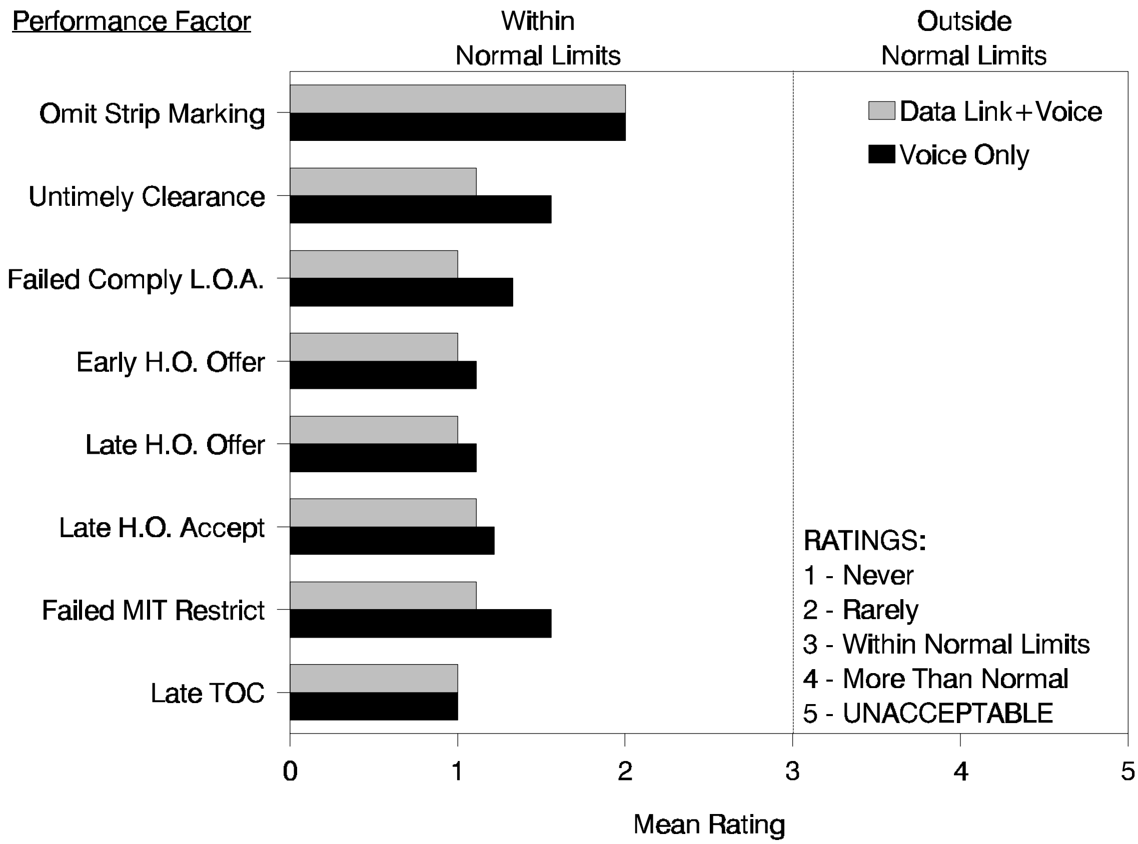

FIGURE 25. SECTOR PERFORMANCE RATINGS IN EXPERIMENT 3

experimental subjects, the controllers also made an absolute rating of each run using a SWAT.

All of the 36 radar and handoff position ratings obtained over the 18 voice-only and Data Link test runs indicated that controller workload was "acceptable" and did not affect the controller's ability to control traffic safely and effectively.

The comparative workload ratings received from the radar and handoff controllers are summarized in figures 26 and 27. As shown in the histograms, none of the controllers staffing the handoff positions indicated that their workload was "much higher" than normal for their position under either communications condition. When using Data Link, the workload ratings varied widely among radar controllers. Three of the radar controllers indicated that their workload was "much lower" or "somewhat lower" than normal, four indicated that it was "about the same" as normal, while two rated it as "somewhat higher." With voice communications only, one radar position rated workload as "somewhat lower" than normal while the remaining ratings indicated that workload was "about the same" as normal for the operational position.

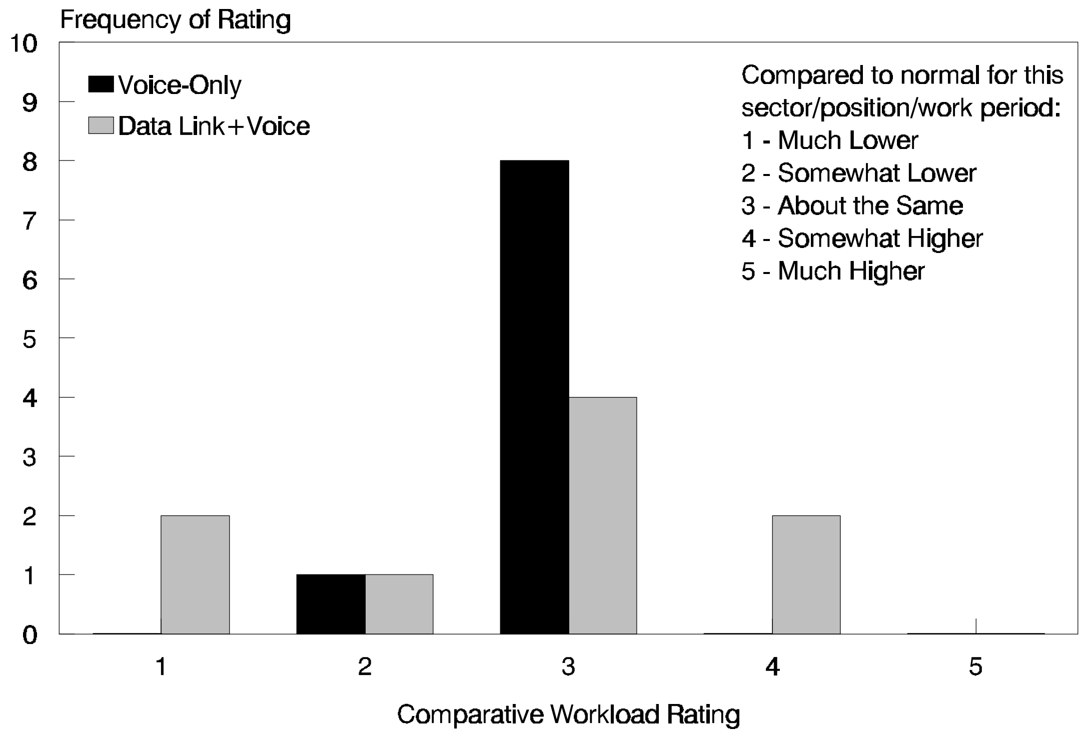

FIGURE 26. COMPARATIVE RADAR CONTROLLER WORKLOAD RATINGS IN EXPERIMENT 3

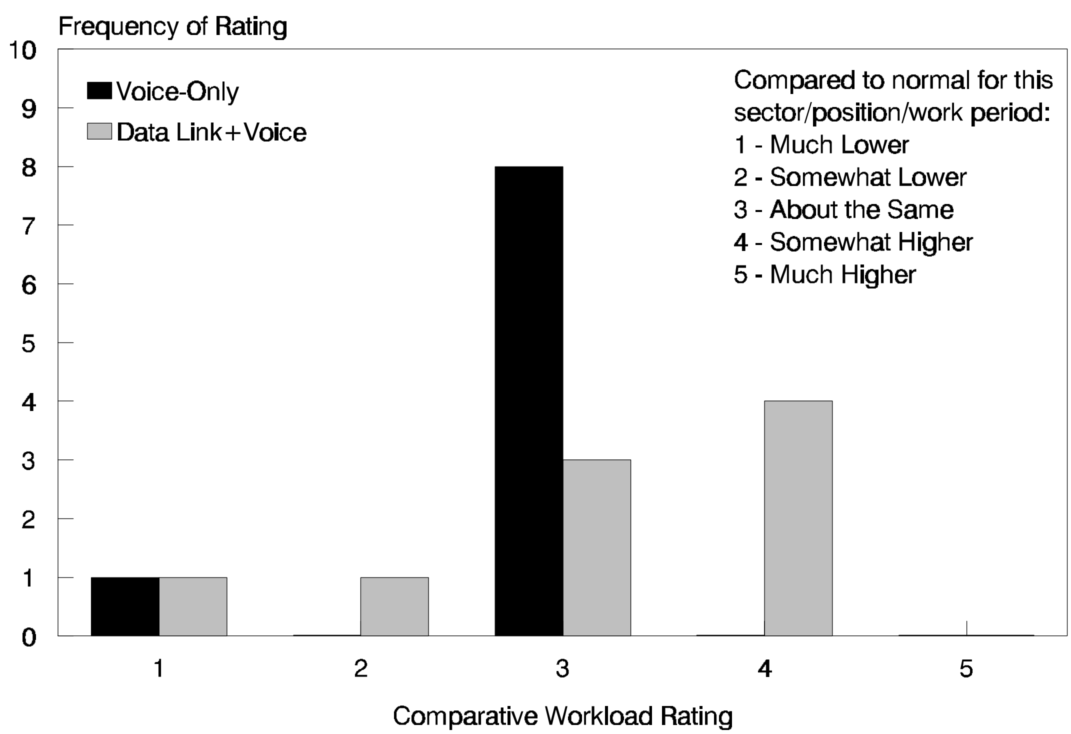

FIGURE 27. COMPARATIVE HANDOFF CONTROLLER WORKLOAD RATINGS IN EXPERIMENT 3

When working at the handoff position, workload ratings with Data Link were also variable. Four controllers indicated that workload was "somewhat higher" than normal, while five indicated that it was either "about the same" as normal or lower. Voice-only ratings were consistent with the radar controller evaluations with a majority of the controllers indicating that workload had been "about the same as normal."

The results obtained with SWAT closely reflected the findings obtained with the comparative ratings. As shown in figure 28, the mean SWAT workload scores for the radar position were higher under voice-only communications than when Data Link was available. The mean scores for the handoff control position were higher with Data Link. The overall wide variability of the ratings on the comparative workload assessment were mirrored in statistical tests of the apparent SWAT effects. The reduction in workload with Data Link for the radar position was statistically significant (t_8=1.86, p=.05). However, the increase in workload with Data Link for the handoff position was not (p=.15).

Two observations about the workload assessments obtained for this experiment are warranted. First, the SWAT scores for both controllers in the MUGZY satellite arrival sector under voice only and Data Link plus voice are much lower than those obtained in the jet arrival positions

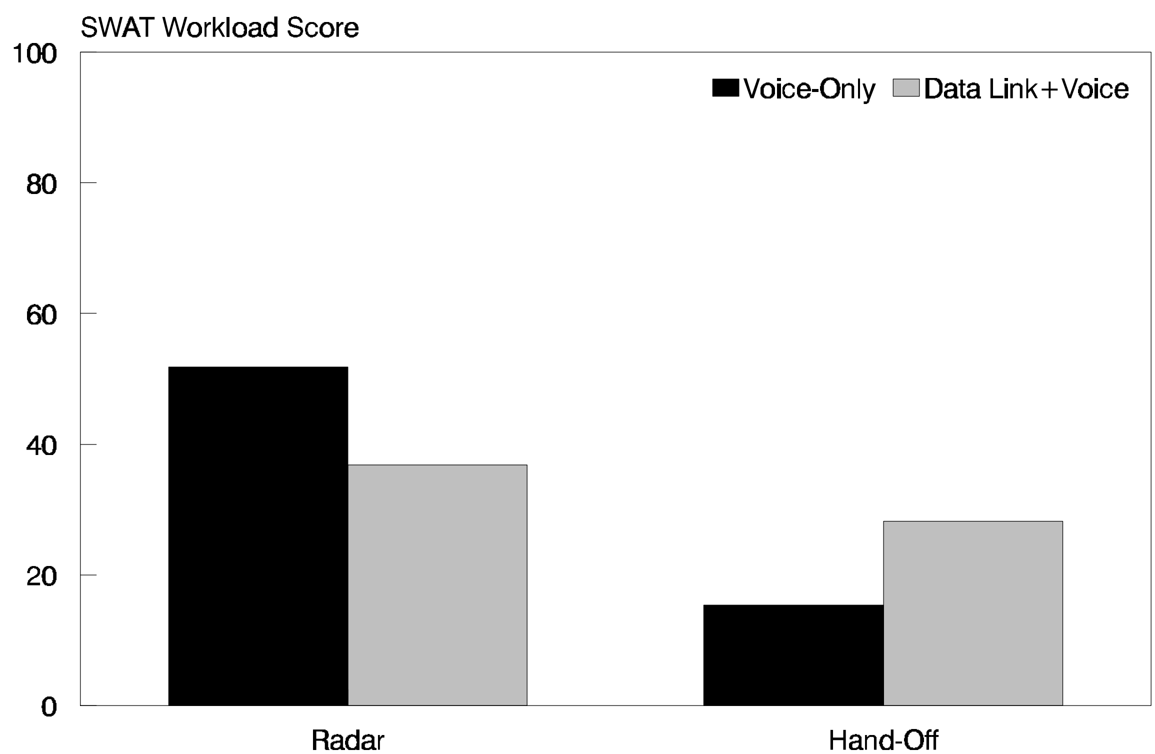

FIGURE 28. SWAT WORKLOAD SCORES IN EXPERIMENT 3

(experiment 2). This difference in reported workload is closely associated with the different air traffic loads in the two scenarios. Second, the workload ratings were also more variable in experiment 3 than in experiments 1 and 2. These wide differences in controller evaluations of workload were similar to the variable safety ratings obtained in this experiment. Overall, they appear to reflect the problems experienced by some controllers in developing and applying effective Data Link task sharing procedures within MUGZY which were not apparent when the supervisors worked with the final controllers on the jet arrival problem in experiment 2. These variations may be indicative of needs for controller team training with Data Link. When considered along with the failure to find significant performance benefits with Data Link, the workload and safety data also may suggest that Data Link's utility is limited for the type of ATC problem that was presented by the Newark area satellite arrival (see section 5.3.6).

<u>5.3.5 Communications</u>.

<u>5.3.5.1 Voice Radio Usage</u>.

Figure 29 illustrates the reduction in voice radio usage that occurred during satellite arrival testing when Data Link communications were

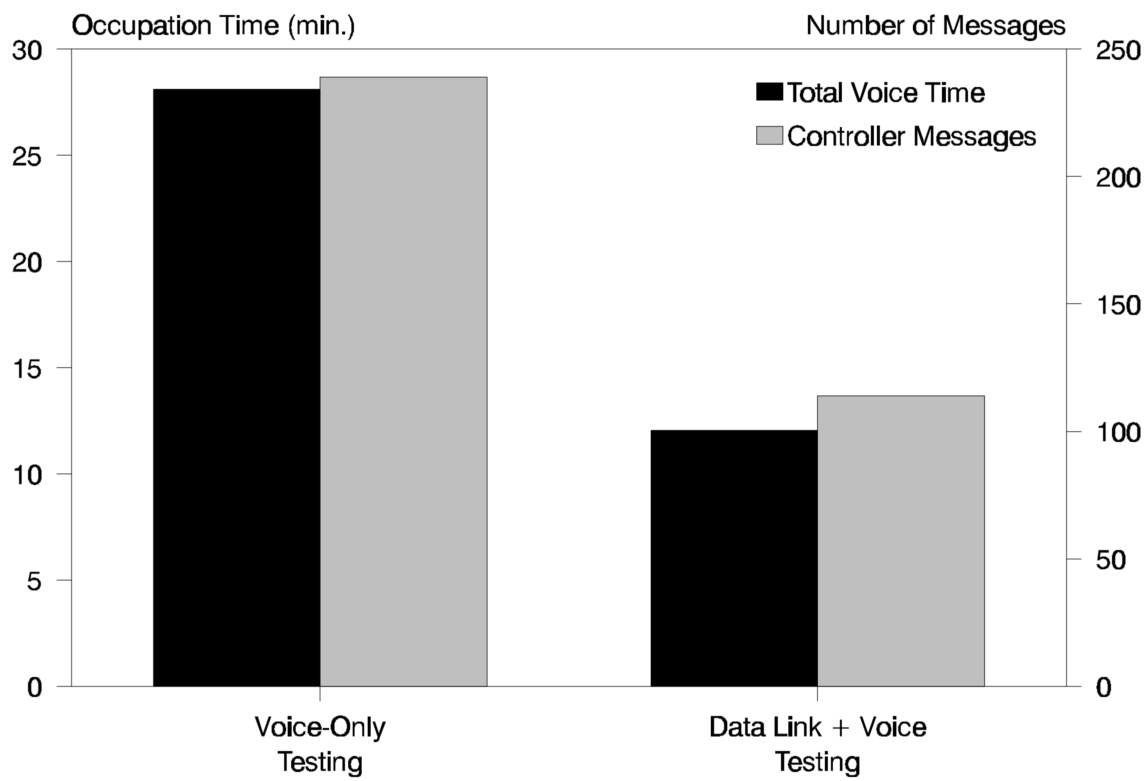

FIGURE 29. RADIO FREQUENCY OCCUPATION IN EXPERIMENT 3

available. As shown in the figure, during voice-only testing, the radio channel was occupied by ATC communications for an average of more than 28 minutes, and the radar controllers sent an average of 239 voice messages to pilots. During Data Link testing, radio channel occupation time for the average test run dropped by 57 percent to approximately 12 minutes. The number of voice messages were reduced by 52 percent to 114.

5.3.5.2 Data Link and Voice Message Content.

Voice radio and Data Link messages sent by controllers were analyzed by grouping them into the 22 mutually exclusive categories of clearances, requests, and informational transmissions to pilots used for experiments 1 and 2. Definitions of the categories used in the content analysis of voice and Data Link transmissions made by controllers are presented in section 5.1.5.2.

Table 5 presents a breakdown of the average number of voice messages transmitted during voice-only testing and the average numbers of voice and Data Link messages sent during Data Link testing. When interpreting this table, it should be noted that comparison of the absolute numbers of messages sent in each category across conditions can be misleading since variable numbers of aircraft were handled by the controllers during the scenario periods.

Overall, it should be noted that the communications requirements of the problem tested in this experiment were much different than those presented by the problems in experiments 1 and 2. The total number of voice messages sent during voice-only testing was approximately 50 percent lower in this satellite arrival problem than in the jet arrival problems.

Comparing voice messages, the table shows that the overall drop in radio frequency occupation with Data Link was attributable to reductions in a broad range of message types. Under Data Link, voice was used less frequently for all types of clearances (including approach), transfer of communications, and responses to initial contact calls.

Examining the distribution of messages between voice and Data Link during testing, the data show that Data Link was used for a clear majority of transfers of communication and initial contact responses. In addition, all clearance types were sent more often via Data Link than voice. As in experiments 1 and 2, the data also show that Data Link was used for approach clearances. Full approach clearances given in a single transmission were rare under either test condition. Unlike the jet arrival

TABLE 5. VOICE AND DATA LINK MESSAGE CONTENT IN EXPERIMENT 3

Message Type	Voice-Only Testing Avg.	Data Link Testing Avg.	
	Voice	Voice	Data Link
Speed	12	4	13
Heading	24	12	21
Altitude	35	11	24
Comb. 2 Part	15	7	7
Comb. 3+ Part	0	0	0
TOC	26	10	20
TOC+	4	2	0
IC Resp.	11	4	23
IC Resp.+	23	4	13
Info.	12	8	0
Route	1	2	0
Correct.	6	4	0
Info. Req.	3	3	0
Other	3	3	0
X Restrn.	0	0	0
Approach Full	2	1	0
Approach Join	21	9	19
Approach Join+	5	3	0
Appch. Partial	21	6	21
Visuals Request	5	9	0
Visuals Follow	1	1	0
Visuals To Apt.	9	10	0
TOTALS	239	114	161

problems, instructions used to establish the aircraft on the final approach course were commonly sent using Data Link. Data Link was also typically used to send the final clearance to execute. The controllers used visual approaches for nearly one-half of the arrivals. These were accomplished using voice radio.

As in experiments 1 and 2, the data also show that, with Data Link, messages required, because of inaccurate communications, were reduced. These included messages to correct, repeat, or clarify a clearance.

5.3.6 Summary of Experiment 3 Findings.

Overall, unlike experiments 1 and 2, this experiment failed to yield evidence for significant benefits of CPDLC. While small improvements in sector performance were obtained in some test runs, others showed no significant changes. Similarly, controller evaluations of safety and workload exhibited wide variability.

This result may have been produced for a variety of reasons. As noted in section 5.3.4, the data suggest that some of the variation may have been caused by inadequate procedures for sharing Data Link tasking between the radar and handoff controllers. Since successful task sharing did occur in experiment 2 in the jet arrival problem, this procedural issue is probably not indicative of a general problem of applying Data Link to the terminal area.

A larger issue which may account for the absence of significant Data Link benefits in this experiment concerns the type of ATC problem that was presented by the Newark area satellite arrival position. As described in section 4.1.2, MUGZY presents an ATC situation which is very different from that occurring in the jet arrivals airspace. In comparison to the jet arrival experiments, traffic volume in MUGZY was much lower, even when additional flights were added to increase test sensitivity. However, MUGZY presented a very complicated problem to controllers because of the numerous airspace entry points and multiple destinations of arriving flights, as well as broader variations in aircraft performance capabilities. Conversely, the jet arrival positions were characterized by very high traffic loads during the rush periods tested in this study. However, traffic flows were more predictable as the controllers worked to merge the arrivals for landing at the single EWR runway in use.

These differences suggest that two different factors may have limited performance in the two problems. In jet arrivals, where traffic counts were high and there were requirements for numerous routine communications, the restrictive voice radio channel became a major problem in maintaining system performance. Thus, the addition of Data Link had the capability to provide the types of significant improvements seen in experiments 1 and 2. In the MUGZY problem, communications channel limitations did not appear to be a primary impediment to performance. Relative traffic counts were much lower in the test scenario, and fewer communications were required. Instead, the complexity of the problem appears to be caused by the effort required to effectively maintain adequate situation awareness with the wide range of crossing traffic, aircraft types, and destinations. Such problems cannot be directly addressed by an expansion of communications channel capacity. Consequently, it is unlikely that Data

Link would have a significant impact. In addition, the results indicating that some controllers had difficulty in effectively sharing Data Link tasking in this experiment are also indicative of a global situation awareness requirement where delegation of communications duties to a handoff controller could threaten effective performance.

5.4 SPECIAL TESTING.

Additional time was scheduled at the end of each session of this study to accommodate requirements for repeating test runs that had been discarded because of simulation system problems. Because not all of the available time was needed for this purpose, it was used to conduct four test runs designed to address secondary study issues. Two test runs were completed in which the level of Data Link equipage in the aircraft sample was reduced from 90 percent to 50 percent. In the remaining two runs, the Data Link initial contact service was eliminated from the message set. In these runs, rather than downlinking an assigned altitude report when entering the sector, the pilots of equipped aircraft used voice radio to perform this function in the traditional manner. The jet arrival scenario from experiment 1 was used for testing in all four runs.

Extreme caution must be observed when interpreting the results presented in this section for three reasons. First, the small number of test runs used to examine these experimental manipulations precludes the possibility of drawing any reliable conclusions regarding their statistical significance. Second, the special test runs were conducted at the end of the study sessions after the controllers had gained considerable experience with Data Link communications, while the comparison runs from experiment 1 were completed on the first testing day. This presents the possibility that any effects of the equipage change or modification of the message set were confounded with system learning effects. Finally, all of the controllers had previously controlled traffic in the same test scenario that was used to address these issues. Thus, specific scenario learning effects also may have influenced the results.

5.4.1 Reduced Aircraft Equipage.

Table 6 summarizes the flight performance data for the two 50-percent equipage runs in comparison to the range of findings for the nine test runs of experiment 1. Inspection of the data indicate that flight times and distances within the sector were comparable to those obtained with a 90-percent level of aircraft equipage. Mean per-aircraft sector entry delay savings in comparison to the voice-only operational baseline appear to have been slightly lower than those obtained under 90-percent equipage.

TABLE 6. 50 PERCENT AND 90 PERCENT EQUIPAGE TEST RUNS

	50% Run 1	50% Run 2	90% Exp. 1 Range
Sector Entry Delay Savings (min.)	.55	1.54	1.89 - 2.16
Time in Sector (min.)	11.10	11.95	11.10 - 15.79
Distance in Sector (miles)	46.67	47.83	49.02 - 59.10

5.4.2 Voice Radio Initial Contact.

Table 7 summarizes the flight performance data for the two-voice initial contact (IC) runs in comparison to the range of findings for the nine test runs of experiment 1 in which Data Link was used for this transaction. Inspection of the data indicate that flight times and distances within the sector border on the low end of the range of findings from experiment 1. However, it should be noted that these apparent differences may be attributable to scenario learning and improvements in Data Link skill at the end of the study. Mean per-aircraft sector entry delay savings in comparison to the voice-only operational baseline appear to have been slightly lower when the initial contact was accomplished using voice radio than when Data Link was used.

TABLE 7. VOICE AND DATA LINK INITIAL CONTACT TEST RUNS

	Voice IC Run 1	Voice IC Run 2	Data Link IC Exp. 1 Range
Sector Entry Delay Savings (min.)	1.54	.56	1.89 - 2.16
Time in Sector (min.)	9.87	11.61	11.10 - 15.79
Distance in Sector (miles)	43.54	49.17	49.02 - 59.10

Overall, comments from the test participants regarding the effect of eliminating the use of Data Link for initial contact were negative. During debriefing the controllers and supervisors indicated that, if they were required to verbally respond to the voice “check-in,” much of the valuable use of Data Link, as aircraft entered a sector, would be sacrificed.

With Data Link, the controller’s response to the aircraft’s downlink could include an uplink of routine terminal information and/or an initial clearance involving minimal interference with other duties. With the voice response to the initial contact call, the controllers indicated that it would be more efficient to include the additional information in the radio message rather than sending a separate uplink. However, this would result in an interruption that was eliminated with Data Link.

A second opinion expressed during the debriefing was that some of the efficiencies and delay reductions gained with Data Link would be lost if the IC service were removed. In the current terminal environment "frequency management" is often necessary to prevent congestion. One common strategy for achieving this when traffic is heavy is to delay handoff acceptance in order to delay the requirement to respond to the initial contact call. It was noted that, during the main experiments of this study, this strategy was not necessary because the controller used Data Link for initial messaging and was able to maintain a clear radio frequency. The controllers indicated that this permitted earlier handoff acceptance and subsequent earlier arrival of aircraft in the sector.

5.5 FLIGHT SIMULATION.

The flight simulation sub-study performed in conjunction with this benefits study produced results which directly addressed requirements for the pilot Data Link interface for terminal CPDLC and for effective flight deck and controller-pilot Data Link procedures. The detailed findings of the study are presented in appendix C of this report. The conclusions and recommendations derived from the sub-study are summarized below.

- Data Link in the Terminal Area from the Pilot's Perspective

The ATC Data Link communications in this study were used as a direct substitute for voice. The pilots in general were in favor of Data Link in the terminal area and saw some benefit, but some did not and had many issues of concern with its use. The use of Data Link, Flight Management System (FMS) procedures, and the Data Link applications of the future need to evolve towards a common goal as defined by the Free Flight initiatives.

- Flight Deck Implementation for Terminal ATC Data Link

The way that the pilot is presented with ATC uplinks and responds to those uplinks is critical to the acceptability of ATC Data Link in the terminal area. ATC uplinks should be displayed to the pilots without requiring crew action. Pilots should be able to respond to uplinks with a single button push.

- Pilot-Controller ATC Procedures

This test replaced some voice transmissions with Data Link. Data Link usage procedures need to be established similar to published procedures currently in use for radio, IFR with loss of radio, etc. These procedures should be evolutionary in nature but based on current published procedures. Pilot-Controller Data Link procedures should recognize that Data Link is a new technology that brings new capabilities to the air traffic environment.

Established procedures will allow both pilots and controllers to form expectations about when and how Data Link will be used in a typical flight. Pilot-Controller Data Link procedures should not require pilots to perform additional high workload duties in the terminal environment.

- Flight Crew Procedures

The proposed procedures used in the test worked fairly well with crews that used good Crew Resource Management (CRM) techniques. Many pilots felt that procedures should be standardized between airplane models.

- Training and CRM

Data Link is a new technology and an additional airplane system that is not familiar to pilots. Because Data Link is a new technology, training is a significant issue. This test showed that even highly experienced pilots who read and speak English as a first language can be confused in a mixed voice/Data Link environment.

Pilots reported that they worked more with the other crew member during the Data Link runs, which is good, but also indicates that training of CRM aspects of Data Link procedures is necessary. Good CRM procedures require both pilots to be aware of input that either pilot makes in the FMC. Pilots made numerous comments on uplinks interfering with FMC/CDU functions. The addition of the Data Link communication system in the CDU will require additional CRM training to integrate Data Link into normal crew procedures.

- Recommendations

Additional testing is recommended to determine the overall acceptability of the use of ATC Data Link over the entire flight. Additionally, an effort must be made to include FMS approaches in the test scenarios, like the approaches currently in use or test at several airports (KSEA, KORD). It was easy for some pilots to focus on what they saw as the "misuse" of Data Link in a pure radar vector environment. Pilots that felt that Data Link was misused in this environment did not always see beyond that point when evaluating other points of Data Link.

Any future studies must be of the same high fidelity as this test. Comments were made that this was the most realistic simulation that several pilots had ever seen. This realism contributed positively to the quality of the comments and ratings from the pilots.

5.6 CONTROLLER DUTY PROFILES.

In experiments 2 and 3 of this study, the radar controllers could receive assistance from either the supervisor (experiment 2) or a dedicated hand-off controller (experiment 3) during voice and Data Link test trials. Since this study was the first in which terminal Data Link communications were tested at positions staffed by a control team rather than a single radar controller, data were collected to identify the procedures adopted by the teams to accomplish communications and other ATC tasks.

The duty profiles completed following each test run provided information on how the two controllers allocated tasks. Analyses of the position duty profiles were performed on average scores. These scores were derived by transforming ratings on the 5-point scale ranging from “never my duty” to “always my duty” to numeric values of 0 to 4, respectively.

- Experiment 2

Average duty profiles under voice and Data Link testing for the final radar controller and the supervisor are presented in figures 30 and 31.
As expected, the figures show that all air-ground communications were conducted by the radar controller under voice-only conditions. However, when Data Link was available, the controllers departed from the traditional standard of a single controller communicating with aircraft in a sector. The controller and supervisor used the two communication channels made available with the addition of Data Link by distributing communications tasks between them.

In addition to communications tasks, the duty profiles indicate that other position duties were shared differently under voice-only and Data Link plus voice communications. With Data Link, the radar controllers reported reduced occupation with tasks ranging from offering and accepting hand-offs to flight strip marking. The supervisors reported increased involvement with monitoring the radar display for aircraft conformance with clearances and conflicts, and with position housekeeping and strip marking duties.

From a teamwork perspective, the data also offer evidence for increased participation of both controllers in operating the position with Data Link.

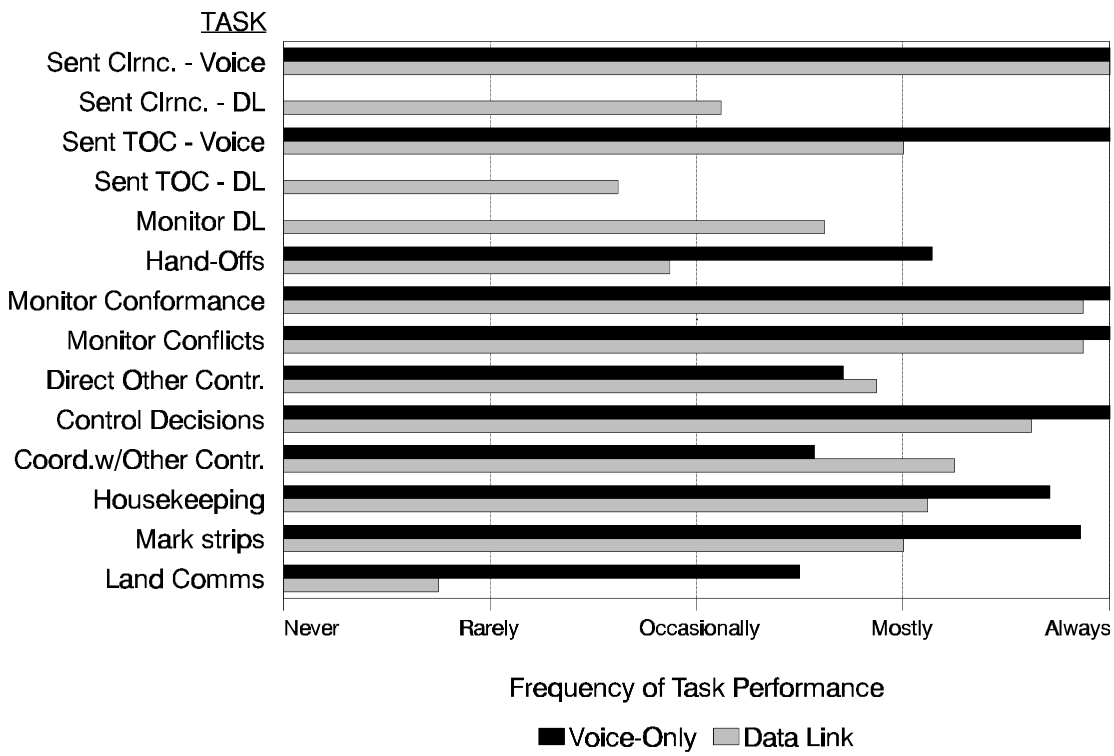

FIGURE 30. FINAL CONTROLLER DUTY PROFILE IN EXPERIMENT 2

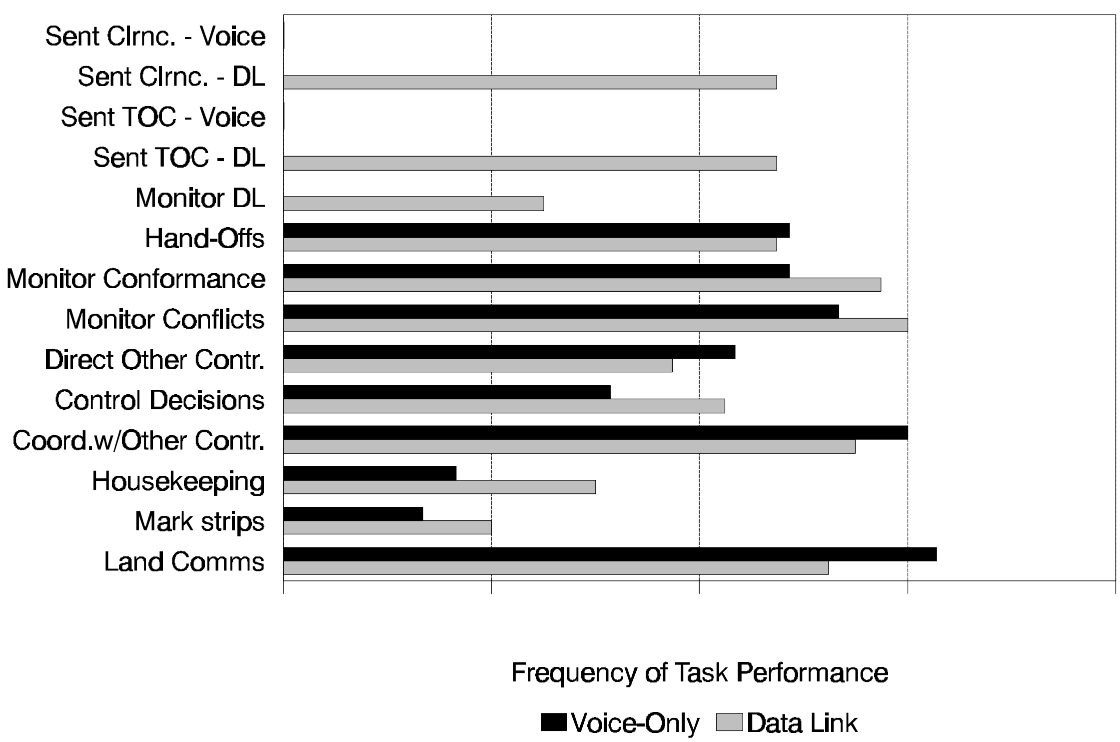

FIGURE 31. SUPERVISOR DUTY PROFILE IN EXPERIMENT 2

The radar controllers indicated that they no longer made all control decisions and spent more time coordinating with the assistant. Likewise, the supervisors reported more involvement in control decisions with Data Link.

- Experiment 3

The average duty profiles for the radar and handoff controllers at the satellite arrival positions are shown in figures 32 and 33. Inspection of the figures shows a similar trend to that seen in the jet arrival problem of experiment 2. During Data Link testing, the controllers shared communications duties, with the handoff controller sending Data Link clearances and transfer of communications messages. However, in this experiment, the level of communications task sharing varied greatly among pairs of controllers.

Other position tasks also were distributed differently with Data Link. The radar controllers reported offering and accepting handoffs, monitoring the radar display, housekeeping, flight strip marking and performing land line communications less often when Data Link was available. The handoff controllers indicated that they monitored the display for conformance and conflicts, and performed housekeeping and land line communications

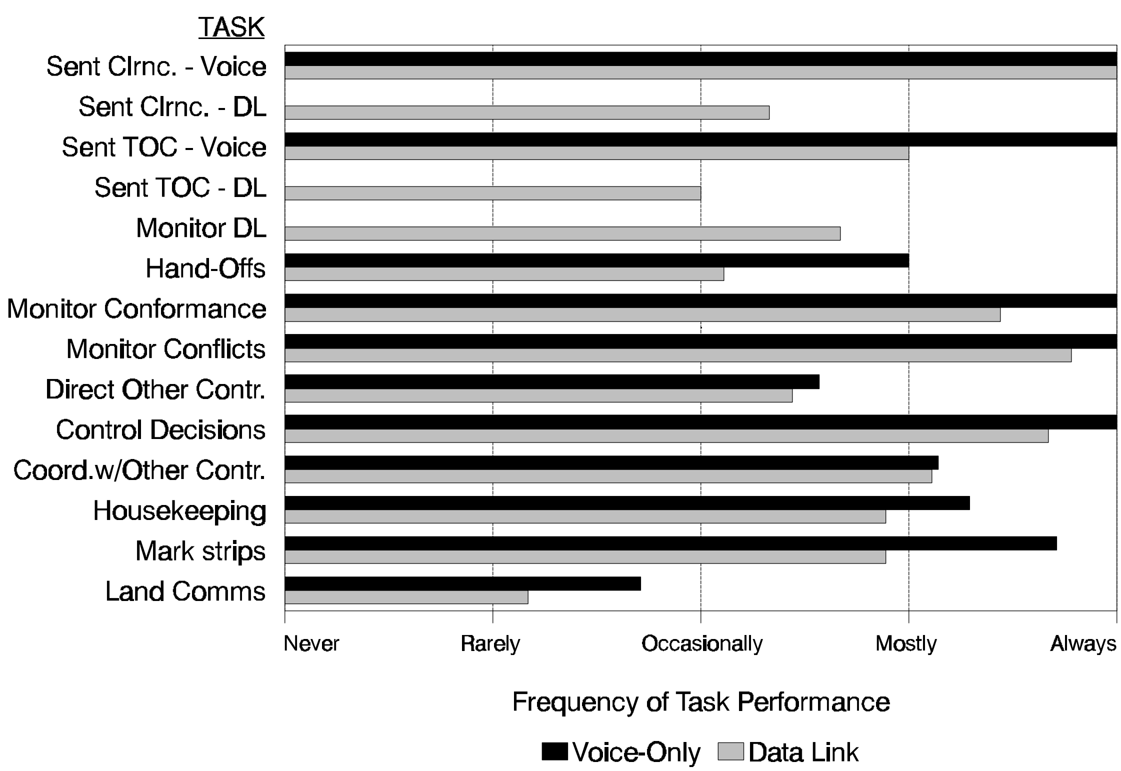

FIGURE 32. RADAR CONTROLLER DUTY PROFILE IN EXPERIMENT 3

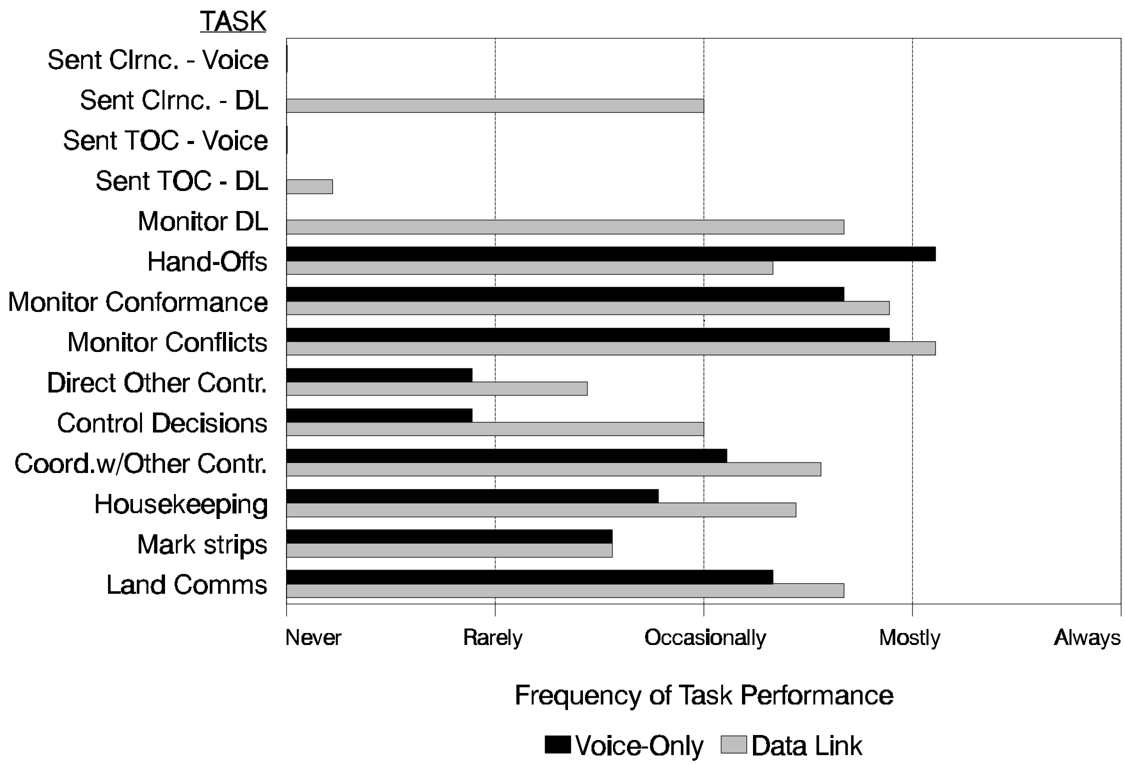

FIGURE 33. HANDOFF CONTROLLER DUTY PROFILE IN EXPERIMENT 3

tasks more often with Data Link. In addition, as in experiment 1, the assistants were more actively involved as members of the control team when Data Link was used. The handoff controllers reported increased participation in control decision making, as well as direction of, and coordination with, the radar controller.

- Discussion

The overall picture conveyed by the duty profiles, and confirmed during debriefing discussions, was similar to that found in the en route benefits study (Data Link Benefits Study Team, 1995). The addition of Data Link both demanded and promoted team cooperation and sharing of duties. In order to make optimal use of the expanded communications channel, both controllers shared communications tasks. This, in turn, required extensive intercoordination between the controllers, and promoted a team approach to monitoring the air traffic situation and decision making. Unlike the current voice-only ATC environment where congested voice communications place assistant controllers in a relatively passive position, the use of Data Link made it possible for the controllers to discuss planned actions and to inform one another about actions that were taken.

5.7 DATA LINK INPUT ASSESSMENTS.

Following each Data Link test trial in all three experiments, the sector supervisors completed a questionnaire regarding their observations of the controllers' Data Link input performance (see appendix A). The questionnaire asked for a basic rating of the number of input errors that were observed ("none," "a few," or "several"). If any errors were noted, the supervisors described how the input errors were handled by the controllers.

The supervisors reported that they had observed no input errors in 20 of the 26 valid Data Link test runs that were completed over the course of the study. During six of the runs, "a few" errors were reported. In no case did the supervisors indicate that they had observed "several" input errors.

For three of the test runs in which errors had been observed, the supervisors said that the controllers had detected the error during the input process and had made the appropriate correction before sending the message. In one remaining case, the controller noticed the error in a Data Link message content/status display, and corrected it with a voice transmission or a second Data Link message. In two cases, the controllers detected an error only after noticing an unintended aircraft maneuver.

5.8 DATA LINK TRANSACTION TIMES.

As discussed in the description of the experimental methodology used in this study, technical time delays associated with uplinking a message to an aircraft and downlinking responses were based on the aeronautical Data Link air traffic service operational performance requirements for the terminal domain. In near-term implementations, the requirements for CPDLC call for a mean one-way transmission delay of 5 seconds, with 95 percent of the transmissions taking 6 seconds or less. The Data Link laboratory approximated this requirement for the study by randomly selecting a transmission time for each uplink and downlink from a rectangular distribution ranging from 4 to 6 seconds. In order to determine the precise range of transaction delay under which the findings of this study were obtained, time recordings were maintained for each Data Link transaction completed in the three experiments.

The measure of delay used for analysis was Total Transaction Time (TTT). TTT is defined as the period of elapsed time from the controller's input to send the message to the appearance of a downlinked response on the controller's display. Thus, the TTT includes the technical system delays associated with uplink and downlink, and the time required by the pilots to detect, process, and respond to the message. Since the TTT is an indicator of the overall delay experienced by the controller, it provides a generic means of examining the impact of transaction duration on ATC performance.

During the study, 9,036 Data Link messages were sent by the controllers which received a pilot response to close the transaction. These responses were generated by the pseudopilots and by the pilots of the two Boeing simulators. Figure 34 presents a frequency distribution of the TTTs obtained during this study. The distribution portrays the data in 2-second increments and is truncated at 60 seconds.

The truncation of the distribution to the left of the figure clearly reflects the minimum technical delays of the simulated Data Link system, with no TTTs below the range 8 seconds. The full distribution of recorded TTTs ranged from 8 seconds to more than 200 seconds. The mean TTT was 16.1 seconds. Seventy-five percent of the transactions had a TTT in the range of 8.1 to 16 seconds.

Of the total number of transactions, approximately 57 percent had TTTs that were 14 seconds or shorter. Approximately B77 percent of the transactions took 16 seconds or less. Ninety-five percent were 28 seconds or less, and 99 percent were 46 seconds or less.

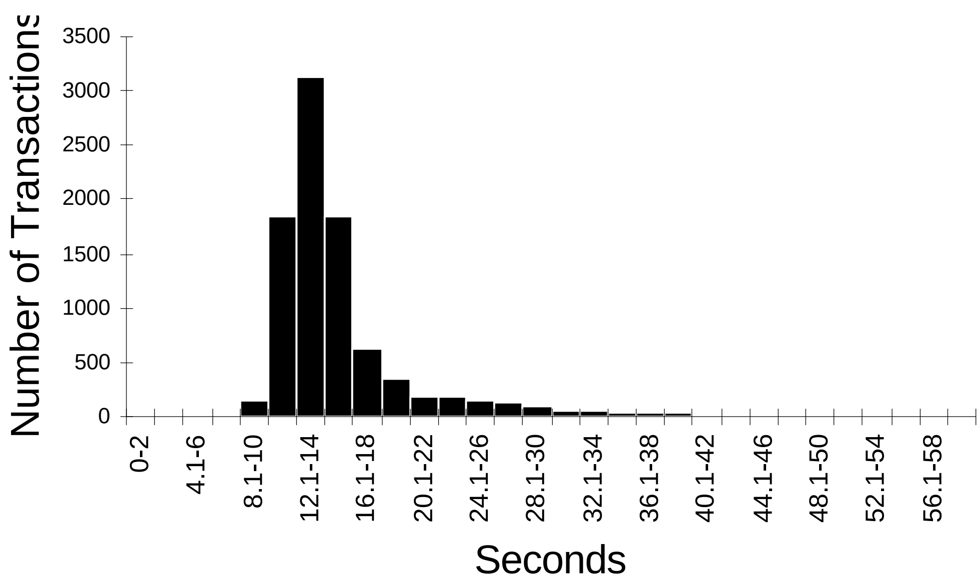

FIGURE 34. TOTAL TRANSACTION TIME DISTRIBUTION FOR 9036 DATA LINK TRANSACTIONS IN THE TERMINAL BENEFITS STUDY

5.9 POST-TEST QUESTIONNAIRE AND DEBRIEFING.

The New York TRACON controllers and supervisors served two functions during this study activity. First, they learned to use the CPDLC system and to apply it during testing in order to produce comparative performance data for the voice and data link environments. Second, as terminal air traffic control specialists (ATCS), they were asked to use their professional background in the operational TRACON and their intensive laboratory experience with Data Link to provide subject matter expert input regarding the system's potential impact and effects.

These data were obtained from structured debriefings and from an extensive questionnaire administered at the end of each of the three study sessions. The majority of the items presented on the questionnaire were formatted as declarative statements. The respondent answered the questions by indicating his level of agreement with each statement on a 5-point scale: (1) Strongly Disagree, (2) Disagree, (3) No Opinion/Neutral, (4) Agree, (5) Strongly Agree. Indications of the statistical significance of the findings discussed below are based on analyses using the Chi-Square statistic where the number of observed responses falling in the two "agree" categories were compared to the number of response in the two "disagree" categories. The test of significance was based on the likelihood that the observed distribution of responses across the agree-disagree dimension differed from a randomly distributed set of responses. All findings discussed below were statistically significant ($p \leq .05$)

- User Benefits

Analysis of the questionnaire items concerned with benefits that may accrue to NAS users indicated that the controllers and supervisors significantly agreed that terminal CPDLC will :

a. result in more timely and consistent ATC service to aircraft in the terminal area,

b. permit controllers to handle a few more aircraft per hour, when airport conditions permit,

c. reduce communications errors that lead to inefficiencies and flight delays.

Eight of the 12 participants also agreed that Data Link will allow controllers to provide additional service to satellite airport users. However, this result was not statistically significant.

During the debriefing sessions, the participants were unanimous in the opinion that Data Link would help if implemented in terminal airspace. Several of the controllers indicated that they had originally been skeptical about the utility of the system, and that their experiences during testing had changed their opinions.

- ATC System Productivity

The participants indicated significant agreement with assertions that Data Link will:

a. improve the reliability and efficiency of ATC communications,
b. make the ATC system more productive, and
c. increase the ability to make efficient use of available airspace capacity.

While not statistically significant, 7 of the 12 respondents also agreed that Data Link will permit the controller to handle more aircraft. Two had no opinion on this assertion, and two disagreed. This range of opinions was also reflected during the debriefing discussions. The controllers noted that, because of airspace design and traffic flows in the Newark area, they did not feel that Data Link would increase maximum airspace capacity. However, they agreed that Data Link would provide them with the ability to resolve many of the problems that currently cause delays and regularly prevent actual system performance from reaching optimal levels.

- Controller Benefits

The participants expressed strong and significant agreement with assertions that Data Link will:

a. be a useful tool for terminal controllers,

b. help by simplifying the task of sending routine, repetitive messages,

c. provide the controller with more time to think and plan future actions,

d. reduce the number of requests for repeats of messages from pilots,

e. give the controller more time to coordinate and plan with colleagues during busy work periods,

f. permit controllers to better distribute workload and avoid too many simultaneous tasks,

g. provide for more productive use of handoff controllers when assigned to a position,

h. make the voice channel available when needed for a time critical clearance, and

i. help to make the controller's job easier and reduce task-induced stress.

Debriefing comments focused on two factors that the controllers perceived as key Data Link effects on their job performance and effectiveness. First, the participants indicated that working traffic rushes with Data Link significantly reduced controller stress. They described the immediate impact of this stress reduction as providing them more time to think and select appropriate actions. In the long term, they indicated that reduced stress would provide a more consistent ability to effectively handle multiple daily traffic rushes. Potential personnel benefits that they felt may be associated with these effects included reduced requirements for rotations to less stressful control positions, increased career span, and increased trainee success rates in busy TRACONs.

The second important Data Link effect that the controllers felt would improve terminal ATC performance was the ability to make more effective use of handoff controllers assigned to a position during heavy traffic periods. In this study, such assistance was provided both in jet arrival and satellite arrival scenarios. The controllers indicated that the potential for performance improvements with Data Link was very high at control positions where the handoff controller's job under voice-only communications is largely limited to acting as an "extra pair of eyes." In such cases, the two controllers can make optimal use of the communications channel expanded by Data Link. The result is an increased ability to make use of existing controller resources and improved sector performance.

The controllers noted that, during this study, the effectiveness of the two-controller team with Data Link may have been underestimated. They indicated that because of long experience at operating with only one controller communicating with aircraft, the transition to a coordinated team was incomplete during the short period of the study. The controllers emphasized that training and procedures will have to be developed for effective controller coordination with Data Link.

The controllers also suggested that while the Data Link team concept was valuable in the jet arrival problem, less success was achieved in the satellite arrival problem. The complexities of the MUGZY position place high demands on the handoff controller including land line communications and housekeeping tasks. These requirements limited the amount of assistance that could be provided by the second controller using Data Link.

- System Safety Benefits

During debriefings, the controllers and supervisors strongly indicated that the safety benefits of Data Link alone were sufficient justification for its implementation in terminal areas. Individual responses to the post-test questionnaire showed that the group significantly agreed that CPDLC would increase the margin of safety in terminal operations and that operational errors would be prevented. Bases for these opinions were reflected in significant agreement with assertions that:

a. controller-pilot communications errors will decrease,

b. safety problems caused by lost communications, stolen clearances, and readback errors would be solved, and

c. frequency outages and stuck mics would be easier to handle and less dangerous.

The controllers also suggested that these safety improvements would be associated with benefits to traffic flow and airspace productivity. By preventing lost communications during radio outages and reducing serious communications errors, flight holding and delays caused by such problems would be prevented.

- Operational Suitability and Controller Performance Issues

Several questionnaire items were designed to determine controller opinions regarding the impact of the current communications system on their performance and the practical operational issues of Data Link implementation. The group significantly agreed that the voice radio system alone strongly affects the capabilities of a terminal controller during busy traffic periods and can prevent timely communication with aircraft.

With respect to the usability of the Data Link system, the group indicated that:

a. Data Link did not interfere with their ability to monitor traffic and make control decisions,

b. Data Link was easy to learn and that skill would improve rapidly in an operational implementation,

c. the risk of making unrecoverable Data Link input errors is low, and

d. terminal controllers will be willing to use Data Link to send clearances.

The controllers also indicated agreement that a limited implementation of Data Link including only Transfer of Communication and Terminal Information services may improve terminal operations. However, they also expressed significant agreement with the assertion that the full set of services including capabilities to send speed, headings, and altitudes would be needed to get maximum improvements from Data Link in a terminal environment.

- Simulation Fidelity and Implementation Issues

A final group of questionnaire items examined the controllers' and supervisors' opinions regarding the quality of the simulation and the overall value of Data Link. These items solicited written comments which are presented below:

Did the simulation environment and traffic used in this test provide a sufficiently realistic replication of operations in the Newark area of the New York TRACON?

Yes	No
12	0

C - Controller
S - Supervisor

C1 - *It seemed to grasp the way EWR runs, and the amount of traffic we handle.*
C2 - *The airspace and traffic were good simulations but the lack of "experienced" pilots made it difficult. There are bad pilots in the world but not all in one spot.*
C4 - *The simulation was very detailed.*
C5 - *Traffic felt real. You would get up from a heavy push feeling the same.*
C6 - *While nothing is as accurate as live traffic, this simulation was the best I have ever experienced.*
C7 - *The simulation was realistic as to volume and complexity of traffic.*
C8 - *Traffic was heavy and as complex as EWR area.*

C9 - *The simulation represented very closely to what we deal with in the EWR area. Not only the automation, but the pilots did a good job also.*

S1 - *As far as simulations go this is the best I've ever seen.*

S2 - *I work in the EWR sector and I am fully aware of the constrictions of our airspace. This test was an excellent replica of a typical day in the Newark sector.*

S3 - *Very realistic - felt just like being at work.*

Do you feel that the conditions of this test provided for fair assessments of a terminal controller's ability to use Data Link and of the effectiveness of the system?

Unbiased	Made Data Link Look Better	Underestimated
8	0	4

C1 - *Everything seemed to be covered so that no one knew ahead of time what was going to happen.* (Unbiased)

C2 - *It was a simulation only, but real world activities can happen the same way, maybe not as often, but possible.* (Unbiased)

C3 - *It's simple. Data Link works. So lets use it!!!* (Unbiased)

C4 - *Because of the detail of the simulation; however the aircraft would have to respond (to uplinks) as fast as they did in the simulation in order to be used as a controlling tool in the terminal environment; not just an information tool*.

C5 - *Only unreal aspect was the lack of other active sectors surrounding the controller. (Unbiased)*

C6 - *I feel that in the field Data Link would be an even greater asset than anything we could display after just 1 week of use. After some time in live traffic runs, I see this completely changing for the better the problem of frequency congestion. (Underestimated)*

C7 - *The full potential of Data Link will be measured after hand-off procedures are developed and implemented. Data Link will also be more useful as controllers get more accustomed to it.*

C8 - *It would be difficult to determine if the test was unbiased or not. Data Link pilots when given a "T" clearance* (menu selected) *that included a turn-on approach clearance responded very promptly. I do question if this is realistic or not. (Unbiased)*

C9 - *Coming into this test cold and seeing what Data Link could do, I'm convinced. I believe once a controller masters it, is when you'll really see the benefits of Data Link. (Unbiased)*

S3 - *With each simulation, the controllers improved in their ability to use Data Link. Development of standardized procedures, increased experience and additional input from personnel in the field would* *enhance Data Link use and effectiveness. I felt we did not see Data Links full potential. (Underestimated)*

(S2 and S1 did not comment on their ratings)

Do you feel that Controller-Pilot Data Link should be implemented at the New York TRACON?

Yes	No
12	0

C1 - *It will help with frequency congestion.*
C2 - *It does have it's possibilities to improve the system; efficiency and safety*.
C3 - *Data Link is a very useful tool. After working a very busy session using only voice a controller comes off feeling numb, and mentally drained. After the same amount of traffic using Data Link the controller comes off felling fresh like he didn't work hard at all. The benefit of all this is the controller stays more alert and is able to run a more efficient, safer operation.*
C4 - *The safety aspect (communications loss), a way to cut down on repetitive clearances which tie up a lot of wasted time on frequency (checking-in, approach clearances, frequency changes).*
C5 - *Significant improvement in safety. It also expands, and makes more useful, the hand-off positions.*
C6 - *Data Link is to communications what the wheel is to travel. We need this now. Any unnecessary delay would be criminal and unfortunate.*
C7 - *Data Link could enable the controller to have more time to plan his/her sequence and separate airplanes more effectively.*
C8 - *Why ? - frequency congestion - stuck mikes - controller stress*.
C9 - *1. Relieve stress. 2. No lost communications and potential for near miss or worse. 3. Less airspace deviations due to pilots/controllers "stepping" on each other.*
S1 - *Because it would increase safety and capacity and reduce stress and workload.*
S2 - *The test runs proved to me that Data Link would be a most "positive" tool that would, under certain conditions, allow us to handle more traffic. By that, I mean, we would not have to go into a hold as soon as we normally would. However, without a dedicated Data Link Hand-off controller the benefits may not be as dramatic.*
S3 - *Implementation would provide immediate reduction in frequency congestion which would equate to increased efficiency and enhanced safety*.

- Other Comments

C1 - *I think with more practice it could be a useful tool to help run traffic a bit more smoothly*

C2 - *This system, in my opinion, is not the cure all for EWR's problem. I believe this system will provide benefits to us in numerous ways. I do believe that this system will be of great benefit to the rest of the country. EWR tries to put 10 lbs. of ---- into a 5 lb. bucket on a daily basis. I'm not sure if anything will help EWR, but this should not be a deterrent to implementing the system.*

C4 - *I believe the study proved that Data Link can be used in our terminal environment. How it will be used needs to be studied further*.

C5 - *I think that implementing this system should be a "No-Brainer" decision. I want it for reasons I think are self evident. Any controller would. I am still not convinced that you will see less delays in areas like the Newark sector. A sector like that will not get the maximum benefits out of Data Link because of poor procedures and airspace problems.*

C6 - *I am very enthusiastic about the possibilities that this tool offers. After just 1 week of using it we have almost all arrived at the position that we would rather work busy traffic with it than without. Data Link truly made the work much easier than using just voice. There is little doubt that this is a golden opportunity to make the system safer and more capable.*

C7 - *The Data Link benefits study was a realistic model of the Newark area. The testing team was knowledgeable and professional yet tried not to bias the opinions of the testing subjects. Data Link would show immediate benefit after little training on the feeder position on initial check in and by eliminating the lengthy approach clearances. The potential benefits on other positions, especially departure, would be great. The implementation of Data Link would reduce controller workload, stress level and improve safety.*

C8 - *Only working for one week on Data Link, we all became pretty proficient. I believe if given more time the benefits of Data Link would become more apparent. Changes to the menu lists could be reworked to better enhance the system for our airspace. Procedures could be established which would give both hand-off and radar controllers a better idea of where their responsibilities are*.

C9 - *I really believe Data Link would be a big help without any detriments. As I stated above, it would relieve stress and make the safety margin that much higher.*

S1 - *I would like it yesterday.*

S2 - *I am very pleased with what I learned about Data Link - I'm sure it can be a "plus" in the terminal area, even if, a dedicated Data Link /hand-off controller is not available. Once a controller becomes* *familiar with the menu items, he/she will use Data Link to his/her advantage and thus have time (more) to concentrate on the traffic at hand. However, with a dedicated Data Link-hand-off controller assigned to a particular position, the benefits would be much greater.*

S3 - *I see enormous potential for Data Link, especially if tied into traffic management, FMS/GPS initiatives currently being considered. I feel any chance we have to reliably automate functions will enhance safety and efficiency.*

6. BENEFIT ESTIMATION AND AGGREGATION.

The primary goal of this study was to identify and measure some of the benefits that the implementation of controller-pilot Data Link communications would provide to the NAS, its operators, and users. Results of the experiments on arrival traffic at Newark International Airport (EWR) presented in this report objectively demonstrated that controllers using Data Link experienced reduced workload and stress and were able to provide ATC services that improved airspace productivity and efficiency. These effects were reflected in reduced flight time, flight distance and arrival delay in comparison to current operational and test environments using only voice radio communications.

One direct approach to measuring the potential magnitude and significance of some of these findings is to estimate their effects on the economic costs of aircraft operation incurred by NAS users. Several analytical methods and modeling tools which can generate such estimates exist in the public domain and in proprietary form. Many of these are designed to assess the impact of technological improvements and other ATC changes on the system-wide flight throughput and delay. The following subsections present the results of an effort to aggregate, nationalize, and annualize the findings of the present study using one modeling approach.

6.1 APPROACH.

The National Airspace System Performance Analysis Capability (NASPAC) Simulation Modeling System (SMS) was used as an analytical tool. The NASPAC SMS is a discrete-event simulation model that tracks aircraft as they progress through the NAS and compete for ATC resources. NASPAC evaluates system performance based on the demand placed on resources modeled in the NAS and records statistics at 50 of the busiest national airports plus eight associated airports.

NASPAC analyzes the interactions between many components of the ATC system and the system reaction to projected demand and operational changes. The model was designed to study nation-wide system performance rather than localized airport changes in detail. Therefore, airports are modeled at an aggregate level. The model also shows how improvements to a single airport can impact other airports in the NAS by altering the arrival rates.

NASPAC records both passenger delay and operational delay. Passenger delay is the difference between the scheduled arrival time contained in the Official Airline Guide (OAG) and the actual arrival time as simulated by NASPAC. Operational delay is the amount of time that an aircraft spends waiting to use an ATC system resource. Only operational delays were considered in the present application to Data Link.

Traffic profiles consist of scheduled and unscheduled demand for each modeled airport. Scheduled demand is derived from the 1996 OAG. Unscheduled demand is calculated from daily and hourly demand distributions taken from real-world data (Host data and tower counts).

Key output metrics recorded in the model include delay and throughput at airports, departure fixes, arrival fixes, restrictions, and sectors. This reporting is done system-wide and at all modeled airports. Operational delay includes airborne and ground delay. Airborne operational delay is the delay that a flight experiences from competing for airborne ATC resources. Ground operational delay accumulates when an aircraft is ready to depart, but has to wait for a runway to taxi on or takeoff from, or when airspace capacity limitations prohibit the aircraft from departing. Sector entry delay occurs when the instantaneous or hourly aircraft count parameters for that sector are exceeded. Monetary assessments are derived by translating delay into measures of cost to the user by using the Cost of Delay Module. The Cost of Delay Module was incorporated into the NASPAC SMS user interface in 1992. The Cost of Delay Module was used to translate delay into measures of cost to the airlines and user community. The Origin and Destination Survey, Form 41, acquired from the Office of Airline Statistics (K-25), is used to calculate operational delay cost estimates. For this study, data for 1994 were used to determine operational costs. Operational costs include crew salaries, maintenance, fuel, equipment, depreciation, and amortization and are reported by the airlines on a quarterly basis. The data are disseminated into airborne and ground delay costs by carrier and aircraft type.

6.2 MODEL INPUTS.

Improvements in hourly arrival rates observed during the study under Data Link testing were used as the input to the NASPAC model. In experiment 1, the real-world operational baseline data indicated that the controllers using voice communications alone had achieved an effective arrival rate of 40 aircraft per hour. During Data Link testing, the average arrival rate increased by 12.5 percent to 45 aircraft per hour. In experiment 2, where traffic was increased and the comparison was between Data Link testing and a voice-only baseline established in the simulation laboratory, the arrival rate with Data Link rose from 45 to 48 aircraft per hour for an improvement of 6.7 percent. The average improvement with Data Link of 9.6 percent across the two scenarios was used as the primary input to the model.

Three NASPAC model runs were completed to provide estimates of Data Link effects on NAS performance. The first was a standard 1995 scenario developed to provide baseline system delay data under current, voice-only communications. In the second run, the Data Link improvement in arrival rate was applied only to the airport used as the test case for this study (EWR). In the final run, the Data Link improvement was applied to all 58 NASPAC airports to provide an estimate of system-wide effects in a full implementation. For the second and third model runs, Data Link effects were included only for arriving aircraft. No direct Data Link effects on terminal departures and overflights, or on en route traffic were assumed.

The model run which simulated the impact of a national implementation of CPDLC was conducted under the assumption that the average improvement in arrival rate observed during testing at EWR could be validly applied to the 58 NASPAC airports. Justification for this assumption was based on two factors: the similarity among terminal ATC operations across the NAS, and the conservative estimate of potential improvement provided by the Newark area.

Terminal arrival operations in the NAS share many characteristics. Most busy TRACONs are organized in the feeder/final configuration used in the Newark area. Controllers staffing the positions perform similar jobs in accepting handoffs from en route controllers, descending and slowing aircraft, and merging multiple streams of traffic. Finally, the aircraft are turned onto the final approach course, cleared for approach, and handed off to the tower. All of the TRACONs work within the same set of rules for ATC and use standard aircraft separation criteria.

As traffic demands begin to exceed capacity in these situations, frequency congestion becomes a problem. Frequency congestion is not affected by differences in airport location, size, or the number of runways available. Because CPDLC has the capability to resolve this problem by expanding the communications channel, it is not unreasonable to propose that a proportional improvement in minimum arrival rate would be achieved at a majority of airports.

A second argument for applying the results of this study to other TRACON environments is that the Newark area presents an arrival problem that is at the lower extreme of the range of terminal areas amenable to improvement. The Newark area operates under severe airspace and noise abatement constraints, as well as requirements for dealing with traffic associated with other New York TRACON areas. These factors make improvements to the EWR arrival rate difficult to achieve with any technology. Consequently, it is likely that the 9.6 percent increase in minimum arrival rate is a very conservative estimate of CPDLC's impact at other airports when demands exceed their current capacities.

The NASPAC methodology includes a technique for computing annual results based on six standard scenario weather days. The scenario days were selected as representative of varying levels of instrument meteorological conditions (IMC) and visual meteorological conditions (VMC) across the 58 NASPAC airports. To compute the annual results, weighting factors for each scenario day are applied according to the frequency of occurrence of similar days that were observed in the year 1990. The present analysis was based on averaging three stochastic runs for each weather day. Table 8 shows the weights applied to the six scenario days.

TABLE 8. WEATHER SCENARIO WEIGHTING FACTORS

Percent (%) VMC	Days Per Year
95% - 100%	80.00
90% - 95%	127.50
85% - 90%	86.25
80% - 85%	23.75
70% - 80%	17.50
< 70%	30.00

For the present effort, the Data Link effect of a 9.6 percent increase in hourly acceptance rate was applied only under IMC conditions. This increase was not permitted to exceed the current maximum VMC arrival rate for any of the airports.

6.3 RESULTS.

Table 9 presents the outcome of the NASPAC analysis. When interpreting this table it should be noted that the findings represent a conservative NASPAC estimate of terminal CPDLC benefits. The delay and dollar cost savings are based solely on the airborne and ground delay changes caused by competition for ATC system resources (operational delay). The major costs of passenger delays which reflect the cascading effects of flight itineraries which are late on any of their flight legs are not included in the calculations. In addition, although Data Link communications are likely to improve performance at terminal departure positions, no CPDLC effects were assumed for these positions.

TABLE 9. ANNUALIZED SYSTEM-WIDE OPERATIONAL DELAY AND NAS USER COST WITH TERMINAL CONTROLLER- PILOT DATA LINK COMMUNICATIONS

	1995 Voice Radio-Only Baseline	Data Link at EWR Only	Data Link at 58 NASPAC Airports
Operational Delay (hours)	1,240,047	1,220,604	1,164,433
Total Cost of Delay	$1,607,370,442	$1,568,812,133	$1,454,902,340
System-Wide Delay Savings (hours)	-------------	**19,443**	**75,614**
System-Wide Cost Savings	-------------	**$38,558,309**	**$152,468,102**

As shown in table 9, the baseline run indicated that operational delays exceeded 1.24 million hours for the 10,179,00 flights modeled during 1995, and that associated costs to aircraft owners and operators exceeded 1.6 billion dollars. The second column of the table depicts the system-wide impact of adding CPDLC only to the terminal arrival airspace tested in the benefit study experiments. When Data Link was implemented at EWR, the total number of hours of delay was reduced by 1.5 percent (19,443 hours). The associated direct airline operating expenses were reduced by 2.4 percent system-wide for this implementation at a single major airport.

The third column of the table presents the results of installing terminal CPDLC at all of the 58 NASPAC airports. In this simulation of a full implementation, operational delays were reduced by 6.1 percent (75,614 hours) in comparison to the 1995 baseline under voice-only communications. System-wide costs of these operational delays to NAS users were reduced by over $152 million annually or approximately 9.5 percent with Data Link.

Overall, the results of the NASPAC analysis showed that the largest reductions in operational delay were attributable to airports which regularly experience traffic demands which exceed their acceptance rate. These airports included Logan International (BOS), Newark International

(EWR), New York LaGuardia (LGA), Chicago O'Hare International (ORD), Detroit Metropolitan (DTW) and Minneapolis-St. Paul International (MSP). Additionally, the data show that the majority of the benefit achieved with Data Link was derived from the ground component of operational delay. These delays accumulate when traffic prohibits aircraft from departing or when aircraft must wait for an available departure runway. Thus, although no direct effects of CPDLC on handling of departure traffic were included as inputs to the model, the increased arrival capacity improved performance in this domain by providing more time for departure processing.

In evaluating the benefit projections discussed above, it should be noted that other modeling and analytical techniques may use different approaches and operate under alternative assumptions than those adopted for this NASPAC simulation. However, as described earlier, the most conservative available options for measuring aircraft delays were used in the modeling exercise, and the basic input data on Data Link effects were derived using extremely high fidelity, manned simulation research findings rather than analytical methods.

It should also be noted that this analysis addressed only one dimension of CPDLC's potential benefit. The estimated cost savings to NAS users are restricted to those produced by implementing Data Link in the terminal environment for arrival traffic. They do not include economic benefits that would directly accrue to the ATC system, terminal benefits at departure positions, or any of the benefits that are associated with en route or tower CPDLC. Finally, the beneficial effects on safety and controller workload that were demonstrated during this study must be added to these economic projections when evaluating the total impact of Data Link implementation.

7. CONCLUSIONS.

The results of the study presented in this report support the following conclusions regarding the effects of controller-pilot Data Link communications in terminal airspace.

a. The real-time, manned simulation experiments performed for this study show that the implementation of Controller-Pilot Data Link Communications (CPDLC) in a terminal air traffic control (ATC) environment can significantly reduce flight delays, improve airspace productivity, enhance safety and reduce controller workload and stress. Specific conclusions drawn from the experiments are outlined below:

1. The study supported the hypothesis that supplementing the voice radio system with Data Link in the operational jet arrival airspace of the

Newark area of the New York Terminal Radar Approach Control (TRACON) during arrival rush periods would reduce delays by preventing and/or postponing the requirement from holding off flights in adjacent en route airspace.

2. In comparison to an operational baseline period and to voice-only testing in the simulation facility, testing with Data Link showed that sector entry times for jet arrivals were reduced by an average of 1.36 to 1.98 minutes per aircraft.

3. Flight efficiency also was enhanced with Data Link in the two jet arrival experiments. Once permitted access to the airspace, the aircraft traveled an average of 1.7 to 6 fewer miles over an average of .7 to 3 fewer minutes than when only voice radio communications were available.

4. The results of the two experiments also show that the effective capacity of the jet arrival airspace was improved with Data Link. Expressed in standard measures of capacity, controllers handled an average of .79 to 6.18 more aircraft per hour and landed an average of 2.89 to 4.8 more per hour with Data Link than with voice communications alone.

5. The jet arrival experiments yielded evidence for benefits beyond flight efficiency and airspace productivity. Although more aircraft were handled and delays were reduced when Data Link was available, these results were accompanied by a reduction in controller workload and perceived stress. Controller comments during debriefings emphasized the significance of this Data Link effect and its potential impact on the consistency of controller performance, career longevity, and trainee retention.

6. The jet arrivals experiments also indicated that the margin of safety as judged by ATC supervisors and controllers was increased with Data Link. Furthermore, the data offered no evidence that the improvements with Data Link were achieved by sacrificing performance of any key control position tasks.

7. The satellite arrival experiment addressed operations in a New York TRACON environment serving commuter and general aviation/business aircraft flying to multiple airports. The experiment did not produce significant evidence for reduced delays or improved flight efficiency with the addition of Data Link communications. The data suggest that this lack of significant improvement was attributable to differences in the ATC problems presented by the satellite arrival and jet arrival airspaces. Performance in the Newark area jet arrival airspace was

strongly affected by high traffic volume and associated limitations in the capacity of the communications channel. Conversely, communications requirements at the Newark area satellite arrival position were much lower, and performance appeared to be primarily limited by traffic complexity and high coordination requirements.

8. All three experiments demonstrated the effects of Data Link on voice radio usage and the potential for reduced frequency congestion. With Data Link, average radio channel occupation time by controllers and pilots was reduced from 57 to 70 percent, while the number of voice messages sent by controllers were reduced by an average of 45 to 66 percent.

9. Results obtained when controllers working a handoff position were permitted to share Data Link communications tasks with the radar controller provided evidence for increased utility of the communications channel expanded by Data Link and for enhanced controller productivity. These findings also strongly indicated that procedures and training programs must be developed to promote optimal performance when two controllers participate in Data Link communications at a single control position.

b. The overall conclusion that can be drawn from this study is that CPDLC will provide significant benefits when implemented in terminal ATC environments. As a minimum, all terminal areas will benefit from reduced controller workload and task related stress, as well as an increase in the margin of safety as communications errors and losses are prevented.

In those terminal environments similar to the jet arrival airspace tested in this study, where ATC performance is limited by the restricted nature of the voice radio system, CPDLC will expand the communications channel. The direct effects of this expansion will be to permit simultaneous communication with multiple aircraft, the relegation of repetitive, time-consuming messages to Data Link, and the reduction of radio frequency congestion, making this system continuously available for time-critical clearances. In such situations, CPDLC will eliminate the artificial restriction on controller performance, and (as shown in experiments 1 and 2) make reduced flight delays and improved use of airspace capacity possible. In addition, CPDLC will permit sharing of communications tasks and make more productive use of handoff controllers that are assigned to busy terminal sectors.

c. One of the key operational questions that arose from the en route Data Link benefits study was whether the benefits observed in that environment would be fully realized in an end-to-end flight regime. That is, while increased sector productivity and improved flow may be achievable with CPDLC in en route airspace, it is possible that these gains would be lost or diminished by the limitations of the terminal environment during arrival or departure flight phases. The findings of the terminal Data Link benefits study suggest that improvements in this airspace domain are complementary to the en route results, and that benefits to airspace users and the effectiveness of the National Airspace System (NAS) would be retained and extended.

The en route findings combined with the terminal results summarized above show that the improved traffic flow made possible with Data Link in en route was mirrored by an increased ability to handle arrivals on the terminal side. Likewise, the terminal ground delay reductions made possible by en route traffic flow improvements, appear to be supported by the expert input provided during the terminal study which indicated that en route restrictions are a major cause of terminal departure problems and that CPDLC would contribute greatly to the productivity and effectiveness of terminal departure controllers.

d. The results of the flight simulation sub-study provided valuable information regarding aircrew requirements for CPDLC in the terminal ATC environment. Among the most important of these findings are that (1) an easily operated pilot interface is required to permit timely and accurate responses to controller uplinks, and (2) effective use of Data Link communications will require the development of specific flight deck and controller-pilot procedures.

Practical limitations prevented the flight simulation sub-study from providing a conclusive operational evaluation of terminal Data Link or of its potential benefits to aircrew performance or flight safety. These limitations included minimal pilot training with the Data Link systems, unfamiliarity with normal operations in the test airspace, and the current lack of tested and standardized procedures for Data Link use. Future testing to address these deficiencies and to resolve issues identified during the study should be conducted under similar high fidelity, dynamic simulation conditions.

e. Some of the economic benefits associated with the results of this study were estimated by calculating NAS user cost savings. The National Airspace System Performance Analysis Capability (NASPAC) simulation modeling system was used to assess the system-wide impact of implementing CPDLC at 58 of the busiest national airports. The average minimum hourly acceptance rate improvement of 9.6 percent derived from the experimental results was applied to the NAS and annualized. Results of this sample modeling exercise showed that airborne and ground operational delays would be reduced by 6.1 percent, resulting in a reduction in annual operational costs to NAS users of more than $152 million.

f. NAS user cost savings were the focus of the economic benefits analysis performed for this study. However, the results of the experiments also indicate that CPDLC will supply benefits to the Federal Aviation Administration (FAA) in the form of reductions in the required costs of operating the NAS and of improving its capabilities. The results of this study, and others, indicate that CPDLC will enhance the accuracy of communications and prevent communications errors and losses. The general benefits associated with such an increase in the margin of safety of NAS operations are self-evident. An immediate FAA economic benefit of this improvement will be a reduction in the resources that must be devoted to investigation and analysis of operational errors and deviations induced by communications problems.

The results of this study also indicate that CPDLC will assist the FAA in meeting the requirements of managing future increases in the demands placed upon the NAS. Projected growth in air traffic will increase requirements for air-ground communications. In general, such growth results in a need for more ATC airspace sectors and generates a proportional demand on the finite supply of voice radio communications frequencies. As shown in this study, CPDLC provided controllers with an expanded communications channel that made it possible to handle more aircraft with improved efficiency. Consequently, CPDLC offers the potential to significantly reduce the rate of growth in requirements for additional radio frequencies. In addition, depending on the transmission medium used for Data Link, CPDLC makes it possible to postpone requirements for implementing a Next Generation Communications (NEXCOM) system.

A final group of study results suggests that CPDLC will provide the FAA with benefits in the personnel area. As reflected in measures of reduced flight delays and enhanced airspace utilization, the findings show that Data Link increased controller productivity. These results indicate that CPDLC may have the capability to lower the rate at which staffing levels will have to be raised as traffic demands increase. Furthermore, as shown by the results of standardized workload scales and controller debriefings employed in the experiments, a major effect of CPDLC will be a reduction in the controller stress that is induced by workload in busy ATC environments. These findings indicate that CPDLC has a positive impact on the controller’s abilities to accommodate increased traffic demands. As suggested by the participating controllers and supervisors during this study, such improvements may be associated with more consistent ATC performance, increased career longevity, and reduced requirements for rotation out of busy control positions.

8. RECOMMENDATIONS.

The following recommendations for actions by the Federal Aviation administration (FAA), aircraft owners and operators, and airborne Data Link avionics manufacturers and integrators are based on the results and conclusions of this study.

a. This study produced data which show that the implementation of Controller-Pilot Data Link Communications (CPDLC) will result in significant benefits to arrival operations in congested terminal airspace. These include reduced flight delays, improved use of terminal airspace, an increased margin of safety, and reduced controller workload and stress. The benefits are independent from, and complementary to, those measured in an en route benefits study. It is recommended that the FAA and National Airspace System (NAS) users consider the findings of this study as they perform cost-benefit analyses in support of decisions to invest in the capability to provide and receive terminal CPDLC services.

b. In addition to identifying benefits of terminal CPDLC, this study also served to identify research and development requirements that must be addressed to ensure an effective implementation of terminal CPDLC. While the controller interface for this application of Data Link is very mature and has been extensively tested, it is recommended that additional work be done to develop and test pilot interfaces which are compatible with the performance requirements of terminal communications. In addition, further research is recommended in high fidelity, controller and pilot-in-the-loop environments to develop and test standardized flight deck procedures for responding to Data Link communications and to develop optimally effective controller-pilot procedures.

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APPENDIX A

SUMMARY OF THE EN ROUTE DATA LINK BENEFITS STUDY

RESEARCH APPROACH.

The first experiment of the en route benefits study tested the ability of CPDLC to reduce airport delays that are caused by capacity problems in a high altitude en route departure sector. It was hypothesized that the increased communications capability provided by Data Link would alleviate ground departure delays by permitting the relaxation of spacing restrictions which are routinely implemented on traffic entering the subject sector.

The second experiment tested the ability of Data Link to improve air traffic throughput in an en route sector where saturation is responsible for inefficient processing of aircraft arriving at a major airport. In this case, it was hypothesized that effective use of the combined voice and Data Link capability would improve the timeliness with which aircraft were delivered to the arrival fix, thereby reducing flight costs and arrival delays.

The two experiments employed a case study methodology. Rather than synthesizing scenarios based on a general concept of the types of ATC problems discussed above, test scenarios were built to precisely duplicate air traffic data sample days taken from two airspace sectors within the Atlanta Air Route Traffic Control Center (ARTCC) which currently experience these problems. For the departure case (sector 32, experiment 1), baseline data on the delays experienced by traffic on the sample days were derived from the historical System Analysis Recording (SAR) tapes. The tapes also were used to create Data Link test scenarios which present departure demands identical to those experienced on the sample day. During testing, miles-in-trail (MIT) restrictions were incrementally reduced to determine the capability of subject controllers to handle the increased flow using the combined voice and Data Link communications systems.

For the arrival problem (sector 09, experiment 2), baseline data on aircraft flight paths and arrival delays for the affected sector were computed from information contained in the historical SAR tapes for the sample day. As in the departure problem, the SAR tapes also were used to create Data Link test scenarios that duplicated the original aircraft crossings into the sector. During testing, data were collected to assess sector throughput and flight distance when controllers used a combined voice and Data Link communications system.

In both experiments, additional test runs were completed with increased traffic levels representative of future demand. These data were used in conjunction with estimates generated by a fast-time simulation model to assess the impact of Data Link in comparison to retaining a voice-only system as traffic volumes grow. Furthermore, in both experiments, objective measures as well as controller, supervisor and pilot evaluations were used to insure that any measured benefits were achieved within acceptable limits of safe ATC and aircraft operations. Each of the experiments was replicated three times with different teams of Atlanta controllers who normally worked traffic in the subject sectors.

RESULTS.

Experiment 1

The primary benefit of Data Link communications hypothesized for experiment 1 was a reduction in ground delay for aircraft awaiting departure from Atlanta. The magnitude of this benefit depended on whether the test controllers could safely accept and control the increased traffic density that would occur as the MIT restrictions were reduced on departures entering the sector.

As demonstrated by the absence of aircraft separation violations, and by supervisor, controller, and pilot evaluations of safety, the teams in all three replications of the experiment were able to safely control the air traffic at all reduced spacing restrictions. These included the conditions in which air traffic demands were increased and aircraft were permitted to arrive at the sector with the legal minimum spacing.

Because the subject controllers were able to reliably control the baseline traffic sample with the minimum spacing, a significant reduction in ground delay was achieved. Total delay for the 48 departing aircraft under the 20 MIT restriction that was in force during the sample day rush period was 1,795 minutes, or an average of 37.4 minutes per aircraft. When the use of Data Link permitted the elimination of restrictions, total ground delays for the same aircraft sample dropped to 687 minutes for an average reduction of 23.1 minutes per aircraft (62 percent).

Data Link testing also showed an advantage when the size of the departure traffic sample was increased by 10- percent. Under the 20 MIT restriction normally enforced for sector 32, a 10-percent growth in departures increased total delay by 582 minutes. However, at the minimum 5-mile spacing that was successfully tested using Data Link, the total delay increased by only 197 minutes.

While the primary focus of experiment 1 was Data Link's impact on ground delays, measures of in-flight performance were collected to ensure that any ground delay reduction was not compromised by a loss in the efficiency with which aircraft were controlled in the test sector.

The results showed that the addition of Data Link communications was associated with a reduction in mean aircraft flight time and distance over all test conditions. The average aircraft on the historical baseline day flew 52 miles in the sector over almost 7 minutes. Collapsing across all restrictions and traffic levels and test teams, mean flight distance was reduced to 40 miles over 5.5 minutes during Data Link testing. Evaluation of sample flight track profiles from the baseline Atlanta data and the test trials indicated that this improvement in sector throughput was achieved because the test controllers were able to release the Atlanta departure aircraft to their desired cruise altitudes sooner than their counterparts using voice-only communications, resulting in shorter sector flight times and distances.

Experiment 2

The hypothesized user benefit of Data Link communications for experiment 2 was an improvement in the efficiency with which aircraft would be controlled in sector 09 and delivered to the arrival fix for the Atlanta airport. As in experiment 1, the criterion measures indicated that the control teams in all three replications of the study were able to safely control the baseline aircraft sample in sector 09, as well as the increases in Atlanta arrival traffic ranging from 10 to 40 percent.

Flight efficiency assessments obtained during the test runs completed with the baseline traffic showed that the addition of Data Link communications was associated with a reduction in mean Atlanta arrival aircraft flight time and distance in sector 09. The average arrival aircraft on the historical baseline day flew 111 miles in the sector over more than 18 minutes. In contrast, when under control of the Data Link teams, the average aircraft flew less than 89 miles over approximately 14 minutes.

Evaluation of aircraft track profiles revealed major differences between ATC performance on the historical voice-only baseline day and that achieved by the three teams using Data Link. In all cases, the controllers' primary task was to merge several streams of traffic entering the sector to cross an arrival fix at the specified altitude restriction. On the historical baseline day, the sequence was merged at a greater distance from the fix than during the Data Link test trials. In addition, sequencing at the merging point on the baseline day was accomplished in a tactical fashion, with most aircraft vectored into a holding pattern to attain their positions in the arrival sequence.

In contrast, the controllers using the combined voice and Data Link communications system were able to provide more strategic ATC service which resulted in much more efficient aircraft operation. While some vectoring to achieve sequencing was apparent, none of the aircraft were required to enter holding patterns. Furthermore, many of the aircraft received direct clearances, providing them with “short cut” routes to the arrival fix.

When the traffic sample was increased by 10 to 40 percent, the advantage in sector time was maintained. In comparison to estimates derived from a sector model based on the original traffic sample, the addition of Data Link saved an average of 3 to 4 minutes per aircraft in sector flight time.

Other Findings

The improvements in sector productivity discussed above were associated with direct benefits to NAS users. Economic analyses based on the results indicated that the decreases in air and ground delays would be reflected in significant reductions in annual operating costs for flights in the affected Atlanta ARTCC airspace and for flights in similar en route sectors throughout the NAS.

In addition, the study findings showed that the enhanced ATC service to aircraft was attributable to several factors related to controller performance. First, Data Link alleviated frequency congestion, making the voice radio consistently available to the radar position for time-critical clearance delivery. Second, a majority of standard clearances and other repetitive messages were sent using simplified Data Link inputs. This gave the controllers an ability to devote more time to developing and executing effective control strategies. Fourth, optimal use of the expanded communications capability was achieved by distributing communications tasks among all members of the controller teams, thereby permitting simultaneous messaging to different aircraft. Finally, the increased opportunity for controller interaction and cooperation in communications duties provided by Data Link promoted effective teamwork, shared situation awareness, and group participation in sector planning and decision making.

APPENDIX B

CONTROLLER ASSESSMENT INSTRUMENTS

SUPERVISOR'S POST RUN QUESTIONNAIRE

Part I. Supervisor's Performance Ratings

Please evaluate the ATC operations observed during this test run on the following factors:

1. Errors or omissions in normal flight strip marking.

    a) ______ Never Occurred

    b) ______ Occurred, But Within Normal Limits of Operational Acceptability

    c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

    d) ______ Occurred Unacceptably Often

2. Issued Clearances Later or Earlier Than Appropriate.

    a) ______ Never Occurred

    b) ______ Occurred, But Within Normal Limits of Operational Acceptability

    c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

    d) ______ Occurred Unacceptably Often

3. Failed to Comply with Letters of Agreement.

    a) ______ Never Occurred

    b) ______ Occurred, But Within Normal Limits of Operational Acceptability

    c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

    d) ______ Occurred Unacceptably Often

4. Offered hand-offs Earlier Than Appropriate.

    a) ______ Never Occurred

    b) ______ Occurred, But Within Normal Limits of Operational Acceptability

    c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

    d) ______ Occurred Unacceptably Often

5. Offered hand-offs Later Than Appropriate.

   a) ______ Never Occurred

   b) ______ Occurred, But Within Normal Limits of Operational Acceptability

   c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

   d) ______ Occurred <u>Unacceptably</u> Often

6. Accepted hand-offs Later Than Appropriate.

   a) ______ Never Occurred

   b) ______ Occurred, But Within Normal Limits of Operational Acceptability

   c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

   d) ______ Occurred <u>Unacceptably</u> Often

7. Failed To Meet Miles-In-Trail Restrictions That Were In Force During The Test Run.

   a) ______ Never Occurred

   b) ______ Occurred, But Within Normal Limits of Operational Acceptability

   c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

   d) ______ Occurred <u>Unacceptably</u> Often

8. Sent Transfer of Communication Message to Aircraft Later Than Appropriate.

   a) ______ Never Occurred

   b) ______ Occurred, But Within Normal Limits of Operational Acceptability

   c) ______ Occurred More Often Than Normal For This Sector Under These Traffic Conditions

   d) ______ Occurred <u>Unacceptably</u> Often

Part II. Supervisor's Operational Assessment

1. Did you observe any events during this test run which would have constituted an operational error during actual operations in this sector at the New York TRACON?

______ Yes

______ No

If your answer is Yes, please contact test personnel immediately to initiate analysis of the operational error.

2. Based on your experience with actual operations at this (these) sector(s)under these traffic conditions in the Newark Area, use the scale below to make an overall operational assessment of ATC performance during this test run:

a) ______ The margin of safety was higher than normal.

b) ______ The margin of safety was normal.

c) ______ The margin of safety was lower than normal.

d) ______ Operations were unsafe, and unacceptable.

If you checked c. or d., please explain your rating below. Thoroughly describe the incidents or factors which influenced your judgment.

Part III. Data Link Usage

1. Did you observe any controller input errors in selecting or entering Data Link messages?

    a) ______ I did not notice any input errors.

    b) ______ I noticed a few errors.

    c) ______ The controllers made several errors.

2. If you observed Data Link entry errors, how were they handled? (Check all that apply)

    a) ______ Errors were detected by the controllers during the input process and corrected before sending.

    b) ______ The controllers noticed the error in the Data Block or Status List Display after sending the message. The error was corrected by voice radio or a new Data Link message.

    c) ______ The error was detected only by noticing an unintended aircraft maneuver.

    d) ______ The error was never detected by the controllers.

CONTROLLER POST RUN QUESTIONNAIRE

Part 1. Workload Evaluation

Use the items below to describe the level of workload that you experienced at your position during this test run. These should be ratings of your personal perception of how hard you feel you had to work to perform your duties -- not an estimate based on overall sector loading or traffic count.

1. Rate the <u>absolute level of workload</u> for this test run by indicating the level of loading that you experienced on these three factors.

Time Load

_____ 1. Often had spare time. Interruptions or overlap among activities occurred infrequently or not at all.
_____ 2. Occasionally had spare time. Interruptions or overlap among activities occurred frequently.
_____ 3. Almost never had spare time. Interruptions or overlap among activities were very frequent, or occurred all the time.

Mental Effort Load

_____ 1. Very little conscious mental effort or concentration was required. Activity was almost automatic, requiring little or no attention.
_____ 2. Moderate conscious mental effort or concentration was required. Complexity of activity was moderately high due to uncertainty, unpredictability, or unfamiliarity. Considerable attention was required.
_____ 3. Extensive mental effort and concentration were necessary. Very complex activity requiring total attention.

Psychological Stress Load

_____ 1. Little confusion, risk, frustration or anxiety existed and could be easily accommodated.
_____ 2. Moderate stress due to confusion, frustration or anxiety. Significant compensation was required to maintain adequate performance.
_____ 3. High to very intense stress due to confusion, frustration or anxiety. High to extreme determination and self control were required.

2. <u>In comparison to a corresponding traffic period in the Newark Area</u>, the workload at my position during this test run was:

_____ Much Lower Than Usual

_____ Somewhat Lower Than Usual

_____ About The Same

_____ Somewhat Higher Than Usual

_____ Much Higher Than Usual

3. Overall, the level of workload that I experienced during this test run was:

______ ACCEPTABLE -- did not affect my ability to control traffic safely and effectively.

______ UNACCEPTABLE -- either threatened to, or actually did, impair my ability to control traffic safely and effectively.

Please describe any factors that you feel may have influenced your perceived workload:

Part II. Controller's Operational Assessment

Based on your experience with actual operations at this sector under these traffic conditions in the Newark Area, use the scale below to make an overall operational assessment of ATC performance during this test run:

a) ______ The margin of safety was higher than normal.

b) ______ The margin of safety was normal.

c) ______ The margin of safety was lower than normal.

d) ______ Operations were unsafe, and unacceptable.

If you checked c. or d., please explain your rating below. Thoroughly describe the incidents or factors which influenced your judgment

Part III. Individual Duties (For Use After Runs in Which Two Controllers Staff the Position)

Duty Description -- *Please indicate the extent to which you performed each of the following tasks at your position during this test run. For each duty, place an "x" in the column that best describes your level of task involvement.*

	Always My Duty	**Mostly My Duty**	**Occasionally My Duty**	**Rarely My Duty**	**Never My Duty**
Issued ATC Clearances Using Voice Radio	_____	_____	_____	_____	_____
Issued ATC Clearances Using Data Link	_____	_____	_____	_____	_____
Offered/Accepted Sector Hand-offs	_____	_____	_____	_____	_____
Sent TOC Messages Using Voice Radio	_____	_____	_____	_____	_____
Sent TOC Messages Using Data Link	_____	_____	_____	_____	_____
Marked Flight Strips	_____	_____	_____	_____	_____
Monitored Display for Aircraft Conformance	_____	_____	_____	_____	_____
Monitored Display for Aircraft Conflicts	_____	_____	_____	_____	_____
Monitored Data Link Transactions	_____	_____	_____	_____	_____
Handled Land Line Communications	_____	_____	_____	_____	_____
Directed Other Controller	_____	_____	_____	_____	_____
Made or Participated in Control Decisions	_____	_____	_____	_____	_____
Coordinated Actions With Other Controller	_____	_____	_____	_____	_____
Performed Position "Housekeeping"	_____	_____	_____	_____	_____

CONTROLLER AND SUPERVISOR
POST TEST QUESTIONNAIRE

Based on your general ATC background and the experience that you have had with Data Link during this test, carefully evaluate each of the following statements. Place an "X" in the space that indicates your level of agreement with each statement on the 1 to 5 scale

1. It is relatively easy to learn to use Data Link.

Strongly Disagree		Neutral (No Opinion)		Strongly Agree
______	______	______	______	______
1	2	3	4	5

2. Even after completing the practice period, I made many input errors when using Data Link.

3. The training and practice I received with Data Link were sufficient.

4. I expect that my use of Data Link would improve rapidly with additional experience in a real operational implementation.

5. When I made input errors with Data Link, the system either prevented the uplink OR I caught the errors myself before sending.

6. The turnaround time for Data Link transactions during the test was too long for sending Transfer of Communication (TOC) messages.

7. The turnaround time for Data Link transactions during the test was too long for sending Terminal Information (TI) messages.

8. The turnaround time for Data Link transactions during the test was too long for sending most control clearances (speeds, headings, altitudes).

9. I had no trouble switching between voice radio and Data Link as required to get the job done most efficiently.

10. I sometimes attempted to send Data Link messages to non-equipped aircraft and failed to notice that the message had not been sent.

11. Data Link will be a useful tool for terminal controllers.

12. In today's system, during a traffic rush, the voice radio system can prevent terminal controllers from communicating with aircraft when they need to.

13. Data Link helps by simplifying the task of sending routine, repetitive messages.

14. When busy, a terminal controller using the voice radio alone is significantly affected by limitations of the communications system.

15. A Data Link terminal controller will have more time to think and plan future actions.

16. Data Link should significantly reduce controller-pilot communication errors.

17. The margin of safety in terminal ATC operations will not be increased with Data Link.

18. Data Link will reduce the number of pilot requests for retransmissions (repeats) of messages sent by controllers.

19. The Data Link controller will have more time to coordinate and plan with others during busy work periods.

20. Data Link permits controllers to better distribute their workload and avoid having too many things to do at one time during busy work periods.

21. Data Link won't permit better use of hand-off controllers when they are added to a busy position.

22. I feel that Data Link will result in more timely and consistent ATC service to aircraft.

23. The ATC system should be more productive with Data Link.

24. Data Link should increase our ability to make efficient use of available terminal airspace capacity.

25. If airport conditions permit, terminal arrival controllers should be able to work a few more aircraft per hour with Data Link.

26. Terminal controllers will experience less stress during busy traffic rushes when Data Link is implemented.

27. Data Link makes the voice channel more available when it is needed for a time-critical clearance.

28. The history list effectively reminded me about the content of a clearance sent previously.

29. In general, Data Link will permit the terminal controller to handle more aircraft.

30. Data Link will help to prevent operational errors.

31. Terminal controllers won't be willing to use Data Link to send speed, heading or altitude clearances.

32. The risk of making unrecoverable input errors and sending erroneous messages with Data Link is too high.

33. Just implementing the Transfer of Communication and Terminal Information Data Link services would improve terminal operations.

34. The full set of Data Link services (TOC, TI, speeds, headings, altitudes) is really needed to get maximum improvements in the terminal environment.

35. Data Link interfered with my ability to monitor traffic and make control decisions.

36. Data Link will improve the reliability and efficiency of ground-air communications.

37. Data Link will help controllers to provide additional service to satellite airport users.

38. Data Link will help make my job easier.

39. Data Link will reduce minor communications errors that can lead to inefficiencies and flight delays.

40. Lost communications, stolen clearances, and readback errors are important safety problems that would be solved by Data Link.

41. Having aircraft equipped with Data Link would make frequency outages and stuck mics easier to handle and less dangerous.

Please answer the following questions and briefly explain your answers:

42. Did the simulation environment and traffic used in this test provide a sufficiently realistic replication of operations in the Newark Area of the New York TRACON?

______ YES ______ NO

Why or Why Not?

43. Do you feel that the conditions of this test provided for fair assessments of a terminal controller's ability to use Data Link and of the effectiveness of the system?

______ The test conditions gave an unbiased assessment of Data Link.

______ The test conditions <u>made Date Link look better</u> than it would in the real world.

______ The test conditions may have underestimated the controller's ability to use Data Link and the effectiveness of the system in the real world.

Please explain your answer:

45. Do you feel that Controller-Pilot Data Link should be implemented at the New York TRACON?

______ YES ______ NO

Why or Why Not?

Please add any additional comments or observations that you would like to express:

APPENDIX C

PILOT ASSESSMENTS

(This appendix was prepared by the Boeing Commercial Airplane Company in conjunction with the Data Link Benefits Study Team.)

1. ATC DATA LINK FROM THE PILOT'S PERSPECTIVE.

This experiment was a very high fidelity simulation of the Newark area of the New York TRACON approach control during a busy 1-hour session. The pilots flew the B747-400 and B777 simulators at Boeing using normal airline procedures used in a typical airline cockpit. The two airplanes have different pilot interfaces for ATC Data Link communications. They are the Control Display Unit (CDU) interface in the B747-400 and the Engine Indication and Crew Alerting System/Glareshield (EICAS/Glareshield) interface in the B777.

The results of the flight simulation sub-study provided valuable information regarding aircrew requirements for CPDLC in the terminal ATC environment. Among the most important of these findings are that (1) an easily operated pilot interface is required to permit timely and accurate responses to controller uplinks, and (2) effective use of Data Link communications will require the development of specific flight deck and controller-pilot procedures.

Practical limitations prevented the flight simulation sub-study from providing a conclusive operational evaluation of terminal Data Link or of its potential benefits to aircrew performance or flight safety. These limitations included minimal pilot training with the Data Link systems, unfamiliarity with normal operations in the test airspace, and the current lack of tested and standardized procedures for Data Link use. Future testing to address these deficiencies and to resolve issues identified during the study should be conducted under similar high fidelity, dynamic simulation conditions.

1.1 CDU ATC DATA LINK PILOT INTERFACE (B747-400).

The pilot interface to the Data Link communication systems in the B747-400 is hosted in the Flight Management Computer (FMC) using the CDU as the display unit and keyboard. The full functionality of the system was available for this test.

1.1.1 Uplink Handling.

Receipt of an uplink is annunciated to the pilots by a chime and a memo message, "ATC MESSAGE," on the Engine Indication and Crew Alerting System (EICAS) display. The non-flying pilot selects the "ATC" special function key on the CDU keypad which displays the uplink on the CDU display. The non-flying pilot reads the uplink out loud to the flying pilot. The flying pilot verbally acknowledges and flies the airplane to comply with the clearance. The non-flying pilot accepts the message by choosing

747-400 CDU Implementation

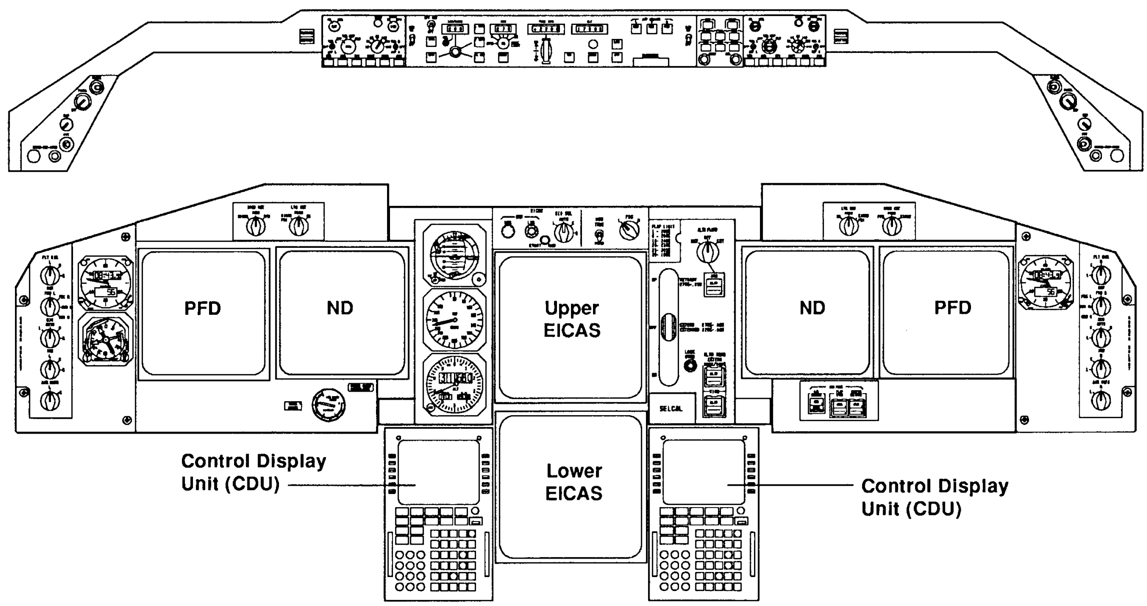

FIGURE 1. B747-400 Flight Deck

the ACCEPT prompt on the last page of the CDU uplink which displays the VERIFY RESPONSE page on the CDU. This page displays the downlink response (usually WILCO in this test) to the uplink as specified in RTCA DO-219 for the uplinked message. After verifying that the response is correct, the non-flying pilot selects the SEND prompt to actually send the downlink response to the controller.

<u>1.1.2 Downlink Report Handling</u>.

In the test, at each transfer of control and initial contact (TOC/IC) between Air Traffic Control sectors, an uplink was received that required a downlink report. The uplink was "MONITOR KNYC ON XXX.XX, CONFIRM ASSIGNED ALTITUDE." (XXX.XX was the VHF radio frequency for the next controller.) This uplink is actually two messages in one uplink. The first message, "MONITOR KNYC ON XXX.XX," requires a WILCO response and is handled as described above. The second message, "CONFIRM ASSIGNED ALTITUDE," requires a downlink report containing the assigned altitude at that moment.

The pilot actions required to send a downlink report are as follows. After the WILCO response described above has been sent, the non-flying pilot selects the REPORT prompt which displays the ATC REPORT page. The pilot then selects the CONFIRM ALTITUDE report which displays the VERIFY REPORT page containing the text of the report downlink. After verifying that the text of the report is correct, the pilot presses the SEND function key which sends the report to the controller. The entire process of responding to the combined uplink (TOC/IC) and transmitting the requested report requires seven keystrokes.

1.2 EICAS/GLARESHIELD ATC DATA LINK PILOT INTERFACE (B777).

ATC Data Link in the B777 is part of the communication system that includes ATC and Company Data Link functions. The communication system uses EICAS to display ATC messages, and ACCEPT/CANCEL/REJECT buttons on the glareshield for response. The Multi-Function Display (MFD) and the cursor control device provide access to the entirety of the communication system, and is therefore an

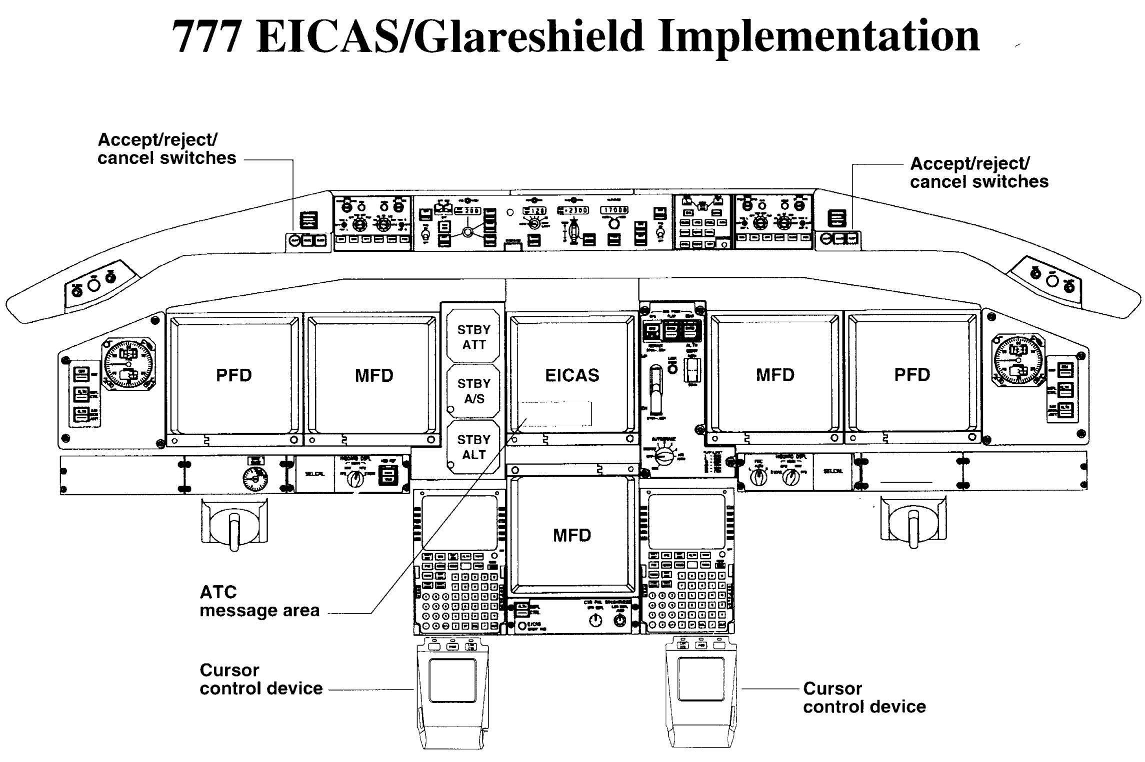

FIGURE 2. B777 Flight Deck

alternative access to ATC Data Link. Partial functionality of ATC Data Link was available for this test. Pilots were able to respond to uplinks but were not able to send downlink reports.

1.2.1 Uplink Handling.

Receipt of an uplink is annunciated to the pilots by a high-low chime and a COMM message "•ATC" on the EICAS display. The text of the uplink automatically appears in a block below the engine instrument indications that is 5 lines of text by 30 characters wide. No crew action is required to display the uplink. An alternative method to view an uplink is also available. To use this method, the pilot chooses the COMM function on the MFD which automatically displays the uplink on that display.

When an uplink is received the non-flying pilot reads the uplink out loud to the flying pilot. The flying pilot verbally acknowledges, directs a response (ACCEPT or REJECT), and flies the airplane to comply with the clearance.

To respond to an uplink, there are ACCEPT and REJECT buttons mounted on the glare shield in front of both pilots which can be used. An alternative method of responding is to select either the ACCEPT or REJECT prompt on the MFD that is associated with the uplink. During this test, the pilots used the glare shield ACCEPT buttons almost exclusively because of their convenience. Pressing the ACCEPT button or selecting the ACCEPT prompt on the MFD automatically sends the affirmative response that is associated with the uplink as specified in RTCA DO-219.

1.2.2 Downlink Report Handling.

As discussed in section 1.2, downlinks were not supported in the simulation for this test in the EICAS/Glareshield interface. When the "MONITOR KNYC ON XXX.XX, CONFIRM ASSIGNED ALTITUDE" uplink was received in the B777 simulator, the crew could only press the ACCEPT button to respond to the controller.

Actual airplane hardware would have required the crew to respond to the uplink "MONITOR KNYC ON XXX.XX, CONFIRM ASSIGNED ALTITUDE" in a manner similar to the CDU interface. The pilots would use the MFD interface to respond to the uplink and send the report on their assigned altitude. The entire process of responding to the combined TOC/IC uplink and transmitting the requested report requires five keystrokes.

1.3 SIMULATORS AND FLIGHT CREW.

1.3.1 Flight Simulation Facilities.

Two flight simulators, a B747-400 and a B777, at the Boeing Airplane Systems Lab in Seattle, WA, participated in a real-time simulation with the ARTS IIIE Lab and the air traffic controllers in the FAA's William J. Hughes Technical Center. Real-time Traffic Alert and Collision Avoidance System (TCAS) targets were sent from the Target Generator Facility (TGF) to both simulators. TCAS target images appeared on the airplane displays along with visual targets appearing "out the window" in the simulator's visual system. The visual targets correlated with the TCAS display so the effect from the pilot's perspective was very realistic.

Communications were simulated via two-way VHF voice and Controller/Pilot Data Link communication (CPDLC) between the simulators and the air traffic controllers. The pilots could hear all other "pilots" on the frequency plus the controller. The fidelity of the communication simulation was very high.

1.3.2 Pilots.

Twenty-four pilots participated in the study, including Boeing Flight Test pilots, Boeing Training pilots, FAA pilots, and airline pilots.

All of the pilots were rated as captains in the B777 and the B747-400 with three exceptions (two pilots were rated in neither the B747-400 nor the B777, and one additional pilot was not rated in the B747-400). It was felt that the lack of current rating for these three pilots had no effect on the test due to the nature of the flying presented in the scenarios (i.e., normal procedures on approaches which did not require a detailed systems knowledge of the airplane). Also, these three pilots all flew with a currently rated Captain. Total flight hours for the pilots ranged from 4000 hours to 22,000 hours. Most of the pilots were not experienced with the Newark area of the New York TRACON airspace.

All pilots flew both the B747-400 and the B777 simulator during the study. A crew typically flew one of the simulators for three consecutive runs, then flew the other simulator for the next three runs. Crews rotated duties (between pilot flying and pilot not flying) in each simulator. This gave all pilots exposure to the Data Link environment in both simulators as pilot flying and as pilot not flying. Also, all pilots hand flew (did not use the auto pilot) on at least one flight in each simulator in order to test the Data Link pilot procedures in both an auto flight and non-auto flight environment.

1.3.3 Pilot Training.

Pilots were given a pretest briefing in small groups. The briefing consisted of viewing the Data Link Program video which was supplied by the FAA, followed by an overview of the test objectives, test setup, flight scenarios and airspace, simulator techniques, an overview of ATC Data Link in both simulators, and a demonstration of Data Link in both simulators. The demonstration for pilots who participated in the last four test sessions contained special emphasis on the CONFIRM ASSIGNED ALTITUDE uplink in the B747-400 because of the complicated nature of the response required.

The training for the pilots in this test was brief for two reasons. First, because of the limited experience in high fidelity simulation of Data Link in the terminal environment with both pilots and controllers participating in the test, there was little experience available to draw on to create a realistic training course. Second, there was no available facility that could simulate the rapid fire rate of uplinks that occurred in this test with an experienced air traffic controller to do the uplinks. Therefore, pilot proficiency in the use of Data Link increased over the first few flights.

2. PILOT POST-RUN ASSESSMENTS.

After each run, which consisted of two flights, the pilots were asked to fill out a questionnaire which dealt in large part with safety issues. This questionnaire captured the immediate feelings on the safety of that run while it was fresh in their minds. Comments varied as the crew gained experience throughout the five or six runs (10 to 12 individual flights) that took place on any given day.

2.1 SAFETY.

The scenario involved extremely heavy traffic, with minimal Data Link training for the pilots, pilots with no ATC Data Link experience, and a Data Link environment with no pilot/controller procedures. In spite of all of these potential problems, the pilots felt that they were safe on 58 percent of the test runs. The margin of safety on those flights was felt to be "typical" or "lower than normal" by most pilots. Comments made by the pilots indicate that there was a difference in their perception of safety based on the pilot interface to the Data Link system. The pilots’ comments mentioned that the CDU interface caused them to be "heads down" far more than the EICAS/Glareshield interface at a critical phase of flight, e.g., very busy terminal airspace.

2.2 MIXED VOICE/DATA LINK ENVIRONMENT.

This test was the first attempt to use Data Link in a very busy terminal environment. There were no pilot/controller Data Link procedures in place for the test. Pilot training in the use of Data Link was minimal. Both pilots and controllers were encouraged to try different techniques and procedures using Data Link. Therefore, it came as no surprise that the mix of voice and Data Link messages caused confusion or doubt in 44 percent of the flights.

There are three issues within this overall score. The first is a problem inherent in Data Link communications -- several pilots commented that it was more difficult to listen for their call sign in a mixed Data Link and voice environment than in a voice only environment. The pilots mentioned that they quickly became accustomed to receiving instructions via Data Link and their attention to the radio dropped. Therefore, when a controller did call with a verbal instruction, they sometimes missed the call. Several pilots felt that pilot/controller procedures should include a method to declare a change of communication mode much like what occurs when moving between a radar and nonradar environment.

The second issue was procedural. Occasionally, Data Link and voice clearances arrived at the airplane simultaneously or very close together. Some uplinks appeared to contradict a clearance received via voice, and some appeared to be redundant to a voice clearance. Pilots did not always know whether to give the uplink or the voice clearance priority and required extra voice transmissions to the controller to clarify the situation. The nature of radar vectors in busy airspace is that there are numerous short transmissions as the controller incrementally moves the traffic towards the final approach course in a highly dynamic environment. There are numerous heading, altitude and airspeed changes that sometimes happen in a very rapid fashion for any single airplane. During the test runs, there were instances of the crew receiving an uplink to turn to a heading followed quickly by a voice call to turn to another heading. Because of the short time interval between the uplink and the voice call the pilots felt that there might be a problem (with the traffic situation) of which they were not aware. The pilots felt that procedures should be developed to address the communications environment that includes a mix of voice and Data Link communications.

The third issue could also be resolved by procedure, or by trust in the system as pilots gain experience with it. Several pilots suggested that they should procedurally check in by voice after they received a Data Link to change frequencies (e.g., MONITOR KNYC ON 128.55). There was one instance where the crew accidentally dialed in the wrong frequency and did not catch the problem for several minutes. In the voice environment, the pilot would have been told to "Contact" rather than "Monitor." The mistake would have been caught as soon as the pilot attempted to check in on the new frequency. He would have received no response, returned to the previous frequency and confirmed the new frequency while still in range of the old frequency. As this test proved, in a mixed voice/Data Link environment, there are far fewer voice transmissions than in a pure voice environment. Therefore, a misdialed frequency that is quiet sounds much like a correct frequency that happens to be quiet because Data Link communications are being used instead of voice.

When this incident occurred in the test, the controller was still able to communicate to the airplane via Data Link. The crew did not realize the mistake until they were told to change to the tower frequency. If the controller would have needed to communicate something urgent via voice, it would have been impossible because the crew had dialed in the wrong frequency.

Questionnaire responses show that the confusion in mixing voice and Data Link was not a result of the message content. The pilots felt that the clearances were both logical and timely in 88 percent of the flights.

2.3 VOICE-ONLY FLIGHTS.

The two pilots experienced with flying B777's into Newark confirmed that the voice only runs were very realistic and accurately simulated a typical heavy traffic situation at Newark. The pilot comments about the voice-only runs showed that they felt safe in 79 percent of the runs. Most flights rated unsafe occurred when the pilots did not hear the clearance correctly and were unable to immediately confirm with the controller because the frequency was too busy. Several pilots commented that the party line was very useful in anticipating what would happen in the near future.

3. PILOT POST-TEST ASSESSMENTS.

3.1 ATC DATA LINK IN THE TERMINAL AREA.

Based on their experience flying both the B747-400 and the B777 simulators in the Data Link and voice-only conditions, pilots were asked to assess the use of ATC Data Link in the terminal area. Sixty-five percent of the pilots in this study were in favor of the use of Data Link ATC communications in terminal area operations.

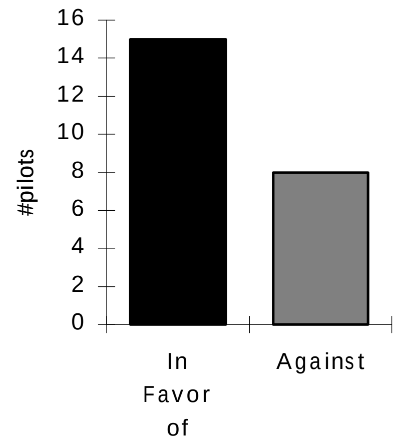

FIGURE 3. Pilot Opinions of Data Link ATC Communications in Terminal Area Operations

Several pilots who favored Data Link in general commented with a caveat that they did not envision Data Link in the terminal area as they experienced in the study. In particular, the use of Data Link for radar vectoring and the amount of Data Link used in the study were questioned.

3.1.1. Pilot Issues and Concerns.

Pilots' comments reveal several reasons for their concern with ATC communications in the terminal area as experienced in this study. Too much heads down time and increased workload was cited most often by the pilots. Some pilots commented specifically that workload and heads down time for the pilot not flying were unacceptable. It is important to note that heads down time and workload were perceived to be different for the CDU and the EICAS/Glareshield interfaces. Written comments show that, for some pilots, the method that ATC Data Link messages are accessed and responded to in the flight deck can make the difference between an acceptable and an unacceptable situation. This is discussed in more detail in section 3.2.

Written comments clearly show that awareness of traffic and of other airplanes' clearances was a concern for many pilots. However, some pilots specifically mentioned that TCAS helped to alleviate the lack of data pilots normally get from the party line. Some pilots felt that their usage of TCAS was different for the Data Link environment than for the voice only environment. All pilots felt that they used TCAS the same amount or more in Data Link communications than they would with voice communications.

It is important to note that TCAS did not always appear to the pilots as totally trustworthy throughout the study. There were several occurrences of spurious TCAS Resolution Advisories in the B747-400 simulator, some that could be explained by anomalies in the TGF targets, and some that had no obvious explanation. This may have affected the pilots' perception of TCAS as a substitute for party line information.

3.1.2 Message Correctness.

Most pilots considered the use of Data Link instead of voice for ATC messages beneficial in terms of the correctness of the message and knowing that the message was intended for their airplane. Several comments stated that there was no call sign confusion with Data Link like there was with voice.

One of the scenarios used in the study involved two airplanes with similar call signs, one of which was assigned to the B747-400 simulator. Two of the flight crews in the B747-400 mistook a voice clearance intended for the airplane with the similar call sign for their own. This result, however, may not be meaningful. All call signs used in the test were not familiar ones for the participating pilots, with the exception of the two airline pilots who were assigned a call sign starting with their own airlines three letter abbreviation on some of their flights. Several pilots indicated that listening for an unfamiliar call sign requires more attention and they could be more likely to mistake a call sign.

3.1.3 Crew Resource Management (CRM).

In the pilots' opinion, Data Link differed from the voice environment in the amount of coordination necessary between crew members. Most pilots indicated that they worked with the other crew member (coordinating, questioning, otherwise discussing clearances) the same or more with Data Link as compared to voice.

All pilots agreed that a CRM procedure for Data Link must be part of training, and that the ATC Data Link interface must be taught in a Line Oriented Flight Training (LOFT) scenario in a flight simulator.

3.1.4 Data Link Usage.

Data Link was perceived to change the manner that tasks were performed in the flight deck. Several pilots mentioned that Data Link forced a serial task performance instead of allowing parallel task performance. In other words, pilots are able to listen and talk on the radio while performing other tasks. Data Link forces them to suspend other tasks while they respond to an uplink.

Pilots perceived Data Link transaction time to be slower than voice. The average pilot response time (the time measured from the annunciation of an uplink to the pilots until the last keystroke required to respond) using the CDU interface (21 seconds) was more than twice that for the EICAS/Glareshield interface (8 seconds), for all simple uplinks (i.e., no CONFIRM ASSIGNED ALTITUDE reports).

In this test, the "MONITOR KNYC ON XXX.XX, CONFIRM ASSIGNED ALTITUDE" uplink required a downlink report. The pilots felt that creating and sending a report is too distracting for a busy terminal environment. They felt strongly that sending a report or any other downlink in this environment would create unacceptable workload in either airplane.

The time it takes the pilot to send a report may also be unacceptable. The average response time (the time measured from the annunciation of an uplink to the pilots until the last keystroke required to respond) for the "MONITOR KNYC ON XXX.XX, CONFIRM ASSIGNED ALTITUDE" uplink and required report was 44 seconds using the CDU interface. Controllers may not always be able to wait that long for a response.

The way that Data Link was used in this study was criticized by several pilots. They felt that the most appropriate use of Data Link is as a compliment to published FMS procedures, not as a substitute for voice for radar vectoring. Predeparture flight plan and clearances, air traffic information services (ATIS), weather information, transfer of communication, NOTAMS, and other routine data transfers were all suggested as more appropriate for Data Link communication than tactical clearances.

3.1.5 Weather.

Weather was not a factor on the actual day used to generate the scenario. However, several pilots mentally projected weather into the test and felt that there might be a significant loss of party line information related to weather. With voice communications, pilots are aware of weather information communicated by other pilots and controllers. Significant situation awareness information such as reports of turbulence etc. are part of the voice party line that could be missed in a Data Link environment. Pilot/Controller procedures on dissemination of weather information must be in place in order to replace this valuable information stream.

3.1.6 Summary of Pilot Comments.

Table 1 shows a summary of the benefits and drawbacks of Data Link as seen in this test from the pilots perspective.

TABLE 1. PILOT COMMENTS ON BENEFITS AND DRAWBACKS OF DATA LINK

Benefits of Data Link
Reduces the chance of missing clearances.
Reduces mistaken call signs.
Reduces the need for repeats.
Able to review messages.
Makes for a quieter cockpit.
Easier to handle multiple instruction clearances.

Drawbacks of Data Link
Too much heads down time.
Increased workload.
Slower to use than voice.
Loss of party line.
Serial tasks instead of parallel.
Easier to miss a voice call in a mixed voice / Data Link environment.
Inappropriate use of Data Link (radar vectors in a terminal environment as opposed to FMS procedures).

3.2 PILOT INTERFACE ACCEPTABILITY (CDU AND EICAS/GLARESHIELD).

The method of ATC Data Link implementation on the flight deck is an important factor in the acceptability of this type of communication in the terminal area according to the pilots participating in this study. In this test, there were two types of pilot interfaces to the Data Link communications system. They were the CDU interface used in the B747-400, and the EICAS/Glareshield interface used in the B777. The B747-400 CDU interface was designed for the oceanic environment and was the first ATC Data Link interface certified for use. The B777 EICAS/ Glareshield interface was designed later and benefited from the lessons learned in the B747-400 CDU interface.

In this study, Data Link was used for radar vectoring (tactical clearances) in the terminal area. The scenario provided an environment to examine how well the CDU and the EICAS/Glareshield Data Link communications systems support Data Link when the pilots are busy and timely communication is imperative. Even if terminal area Data Link is not implemented in this manner, pilot assessment of Data Link in this study is valid for interface acceptability in situations where the time available to respond to uplinks is short. Pilot ratings showed that the CDU interface generally rated unfavorably, and the EICAS/Glareshield interface generally rated favorably when used for radar vectoring in the terminal area.

The way Data Link is used (pilot/controller procedures) can be as important as the flight deck implementation. This experiment tested one end of the spectrum of possible uses for ATC Data Link. As stated elsewhere in this report, the pilots felt that this use of ATC Data Link was not an appropriate use of Data Link. This feeling was expressed and did influence some of the pilot comments addressed in sections 3.2.1 and 3.2.2.

3.2.1 CDU Interface (B747-400).

The CDU presentation of ATC Data Link as used in the B747-400 is certified as part of the FANS-1 package. FANS-1 was designed for the oceanic environment where the time available for pilot response to an ATC Data Link is measured in minutes due to the large separation criteria used therein. In oceanic airspace, separation is procedural and is huge compared to terminal airspace radar separation. For example, at this writing, the separation used on the North Atlantic tracks (NAT) is 60NM lateral, 10 minute longitudinal, and 2000 feet vertical. In terminal airspace, for example, New York, where this simulation took place, adequate response time must be measured in seconds due to much smaller separation criteria. Standard terminal area radar separation is 3 NM lateral/longitudinal by 1000 feet vertical.

The very nature of the CDU creates limits that are difficult to overcome. The display screen is relatively small; some of the longer or multiple element messages used in this study required the pilots to access a second page to view the entire message. This results in several button pushes to read and respond to an uplink. The CDU is located on either side of the throttle quadrant at the forward end of the aisle stand. Performing any function on the CDU, Data Link or otherwise, requires the pilot to lower his/her head to look down, lean forward, and work the keyboard on the CDU. Pilots consider this activity "heads down."

In today's terminal environment where VHF voice radio is used for ATC communication, the pilots normally manipulate the CDU to program the instrument approach that they plan to use and set the final approach reference airspeed. Most pilots try to have this accomplished prior to entering terminal airspace. That way they normally do not have to work with the CDU again unless there is a change to the runway or approach to be used. This technique reduces "heads down time" in terminal airspace.

In this test, there were between 6 and 13 uplinks per run. This meant that the crew had to work with the CDU for a much larger percentage of time for Data Link communications than for voice-only communications. In addition, the crew still had to use the CDU for all of the normal navigation and performance functions (ACARS or company communications was not part of this test). The perception of the pilots was that this large amount of CDU manipulation ("heads down time") was not desirable in highly congested airspace.

There is a potential time-sharing conflict with using the CDU for navigation, airplane performance functions, ACARS (for company communication), and ATC Data Link. Procedurally, ATC communications normally have top priority which leads to a "designed in" conflict with other CDU applications. Several pilots mentioned the serial nature of tasks forced by the CDU interface. This was especially disruptive when they were using the CDU for navigation or performance functions when an ATC uplink arrived. They were forced to stop the navigation or performance function, select the ATC communication function on the CDU and handle the uplink, and then go back to finish the navigation or performance function. The pilots felt that the Data Link interruption could easily cause a pilot to forget to go back and finish the navigation or performance function after the uplink was handled.

In general, the crews felt that the CDU, as implemented, is not an appropriate device to host the Data Link communication system flight crew interface for tactical Data Link messages in terminal airspace. The approach control environment simulated in this test, with its fast pace of radar vectoring, speed control, and numerous altitude changes, overwhelms the CDU interface.

However, several pilots pointed out that if Data Link were used in a different manner, i.e., as a compliment to FMS procedures, instead of simply a substitute for voice communications for radar vectoring, with suitable pilot/controller Data Link procedures, then there would be less Data Link communication required for the operation. Under these circumstances, the pilots felt the CDU interface as implemented could be acceptable for Data Link.

3.2.2 EICAS/Glareshield Interface (B777).

The EICAS/Glareshield using the ACCEPT/REJECT buttons was more acceptable to the pilots than the CDU interface. The uplink is automatically displayed on a dedicated location on the EICAS display in the forward field of vision for the pilots. No pilot action is required to view the uplink other than simply reading it on the EICAS display. For all uplinks used in this study, pilots were able to respond to the uplink with one push of a button mounted directly in front of them. Therefore, the pilots felt that this type of interface was more "heads up" in nature and less restrictive than the CDU interface in the way that it forced them to use the system.

Reports and other downlinks require the crew to use the MFD which is located at the forward end of the aisle stand between the left and right CDUs. A cursor control device is mounted outboard of the CDUs and is used to select command buttons on the MFD. Any time pilots use the MFD for any function, they consider the function to be "heads down." The EICAS/Glareshield (B777) simulation did not require the pilots to send any reports in this test (in contrast to the CDU). It can be conjectured that if CONFIRM ASSIGNED ALTITUDE reports were sent in the B777, some of the same negative aspects of the CDU interface would have occurred (e.g., too much heads down time and increased workload).

4. PILOT RECOMMENDATIONS.

The recommendations below are derived from the comments and responses in the questionnaires as answered by the pilots who participated in this test, based on their experience with the existing FANS I CDU implementation in the B747-400 and the EICAS/Glareshield implementation that will be available in the B-market B777 software loads.

4.1 DATA LINK PILOT INTERFACE.

The EICAS/Glareshield style interface is far more desirable than the CDU style interface for use in terminal airspace where uplink volume is heavy and quick response times are required.

The CDU interface could be acceptable if modified so that most normal length uplink messages could be displayed with one keystroke, displayed on one CDU page, and accepted with one key stroke. A more desirable implementation would allow ATC uplinks to be displayed to the pilots without requiring crew action while still allowing a single button push response.

Any implementation must strive for minimum heads down time.

4.2 DATA LINK IMPLEMENTATION.

Pilot/Controller procedures must be integral with any Data Link implementation.

There should be no manual downlinked reports in busy airspace. In order for a pilot to accurately downlink information to a controller, he/she must review and/or confirm the information prior to sending the downlink. This creates heads down activity which is not desirable in busy airspace. Reports should be eliminated through Pilot/Controller procedures.

Pilot/Controller procedures should be established which procedurally change the active mode of communication between Data Link mode and voice mode.

Data Link should not be used purely as a substitute for voice radar vectors. It should be used in conjunction with Flight Management System (FMS) published procedures such as those envisioned with the Free Flight initiatives. The benefits of relieving frequency congestion may be the same as shown in this test if FMS procedures and Data Link are used together.

A CRM (Crew Resource Management) procedure for Data Link must be a part of the training for pilots to operate in a Data Link environment.

The ATC Data Link interface must be taught in a Line Oriented Flight Training (LOFT) scenario in a flight simulator.