Modeling the Other Half of the Flow

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As we model the movement of aircraft through the airspace, we often focus only on the physical aspects of that movement and its load on geographically based features such as sectors and runways. The movement of each flight is mirrored in the movement of information through an existing or future infrastructure. The FAA, with NASA, is tying those two aspects together in order to better understand "all" the capacity constraints. This especially needed as each improvement we make to the airspace system is based on increasing the need for, flow of, and exchange of information.

This capability, the National Airspace System Simulation (NASSIM) comprises the architecture/infrastructure−modeling component of the National Airspace Resource Investment Model (NARIM). NARIM will provide NASA and the FAA with modeling and analysis capability to examine future airspace operational concepts. The NARIM system consists of three interrelated parts:

- Operational modeling to analyze the movement of aircraft through the NAS to determine the apparent operational impacts those new concepts, and related procedures and/or hardware, will have on the overall performance of the NAS.
- Architectural/infrastructure modeling to assess how procedural/system changes affect the hardware/software components of the NAS infrastructure (both FAA and users), that is the volume and peaks of information flow.
- Investment analysis modeling to cost effectively trade between alternatives for a system, trade requirements within a system and across system and procedural investment alternatives, balance risk, and assess the investment decision as a of part of a total research portfolio.

As a demonstration of concept, the current NASSIM prototype is being used to evaluate the impacts of the introduction of data link as an alternate media for air/ground voice communications. The scope of the current prototype is an ARTCC, a TRACON, and two airports. The multi−center study conducted using these components assessed the impacts of Data Link equipage rates and the differences between FAA facilities on Data Link benefits. The prototype is a discrete−event simulation that functionally models the transmission of communication messages (e.g. ATC instructions and clearances, aircraft clearance requests, etc.) through an air−ground voice communication channel and a digital air−ground communication channel (Data Link). A variety of metrics have been developed and included in the simulation model to capture communications system performance data. The model was configured for three centers (ZDV, ZLA, and ZTL) and executed for multiple Data Link equipage rates.

The discussion will report on the effects of the use of Data Link for en route communications on reducing existing voice channel utilization, voice channel occupancies, and total message delays. How these reductions are measured, through modeling, for all three centers evaluated, for two different Data Link message sets, and all equipage rates (25%, 50%, 75%, 90%) used in this study. The results include impacts on voice channel utilization and highlight voice channel occupancy reductions as well as total message delay reductions. It will include a discussion of how at even low equipage rates there can be significant reductions in voice message delay.

The discussion will also include next steps to improve both the NASSIM capability and the current demonstration. To provide more confidence in NASSIM output, the variance in message rates across sectors by type (such as high, low, transition) requires further analysis. An analysis is being conducted to extend a voice tape analysis previously performed to include analysis of the frequency of miscommunications under voice operations. Since reduction in miscommunications has been identified as one of the potential benefits of data link this data will be used to enhance NASSIM. The current analysis includes total message delay as a performance metric. While this metric provides an indication of the amount of contention that occurs for the voice frequency, the new analysis will include message priorities to enable analyzing the number of critical messages delayed. Finally, numerous proposals have been presented involving the provision of additional data link services (such as graphical weather and traffic information service) as an incentive for users to equip with data link. The impact of these additional services on data link performance needs to be analyzed to determine whether this is a supportable option.

To complete the discussion, there will be an indication of how the NASSIM capability can be extended to improve the tie between the human−in−the−loop and human factor analysis of operational impacts on controller and pilot. The results of these analyses can be included as distributions of behaviors for the controller and pilot components. The components are triggered by these future operational events and extend (in a simplified fashion) the results into a center/multi−center simulation and multiple traffic mixes to look at information loads on both the human and technological components of the National Airspace System.

Background

The genesis of NASSIM arises from two related activities, the modeling of airports using operational simulations and the development of decision tools for the Air Traffic Control Systems Command Center. In both cases the need for an ability to look at the impact of operations on infrastructure across engineering programs and an ability to look at infrastructure eruptions became apparent. As the NAS moves from a ground infrastructure to a shared air−ground infrastructure the need grows.

In the case of the airport modeling, a Task Force Study had shown how a new taxiway and pad would improve the flow of traffic on the airport surface. At the presentation of results, a controller knowledgeable with the airport operations pointed out that a major constraint at the airport was in fact frequency congestion for ground communications and the enhancement would only increase the amount of coordination to get benefit. This concern for the impact on infrastructure and controller has been raised, if not so directly, in many subsequent venues. Our response has often been that we have graphically displayed the proposed changes and asked if in the opinion of our experts this change can be accommodated. As our changes become more fundamental, the need to address this gap analytically has become more important.

The second case was a perceived need for the command center to better understand the impact of infrastructure outages on the flow of traffic and to better plan recovery. The NASSIM prototype was originally designed this purpose. The move to more collaborative CDM and the lack of real time status data to feed the prototype have put that effort on the back−shelf for now, but it did highlight how this capability could be developed and used in a non−real time environment.

The Modeling Environment

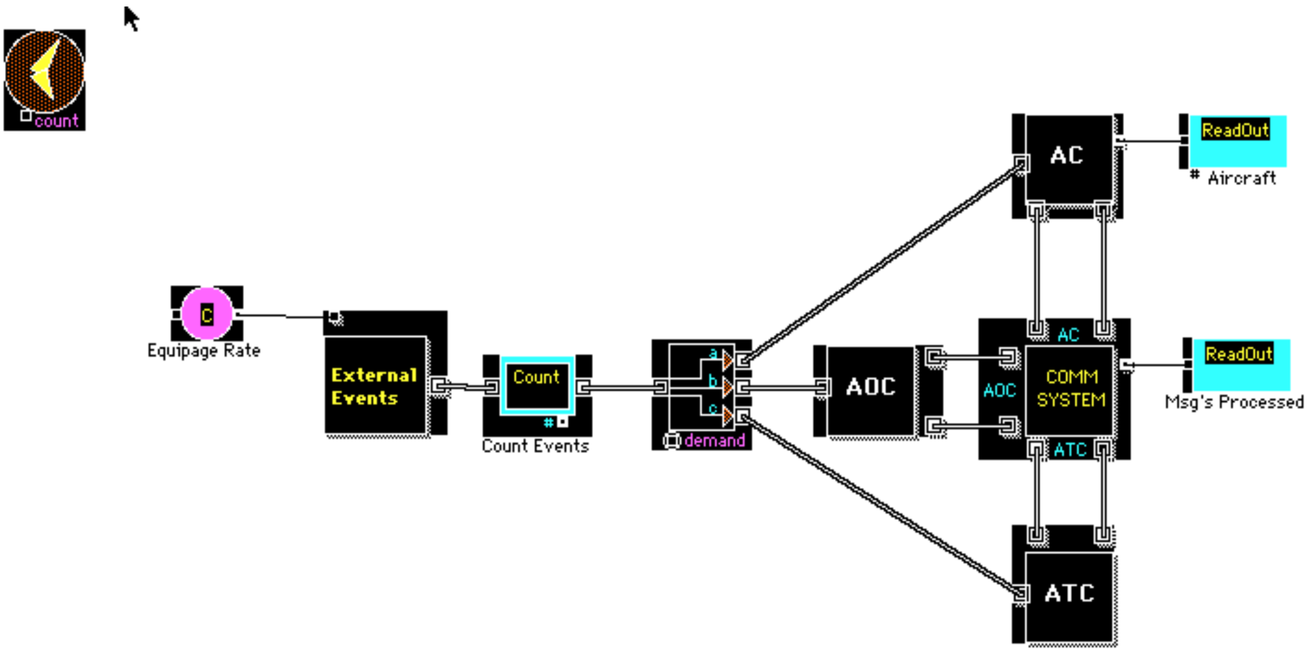

Figure 1− NASSIM Top−level Model

The NASSIM prototype is being developed in Extend^{TM}, a high−level, hierarchical, object−oriented modeling environment. Extend^{TM} provides the capability for building and executing a simulation model. The interactive model editor allows the user to drag and drop simulation objects into the model and to edit the functional performance characteristics of the object. Extend^{TM} has a set of libraries containing commonly needed simulation objects (e.g. queues, decision blocks, random number generators, etc.) that can be used to build a wide variety of simulation models. Extend^{TM} also provides a capability to build custom simulation objects using the built−in ModL modeling language. These objects can be saved to libraries for use in other simulation.

The model, once constructed, can be executed to verify completeness and to conduct analyses. The initiating values and triggering events can be read from file, generated by user−defined distributions or both. Simulation output can be viewed graphically throughout the run and/or saved to output files for subsequent analysis. Using Extend^{TM}, we have constructed five major components for the NASSIM model, the external events generator, the aircraft, the airline operations center, communications links, and air traffic control simulation blocks (Figure 1). Each of these blocks is built up from lower level reusable blocks (Figure 2). The external event generator provides input to the simulation in the form of trigger events. The source for these events (e.g., arrival, departure, and sector−pierce) is the Enhanced Traffic Management System (ETMS) and thus reflects actual National Airspace System (NAS) demand.

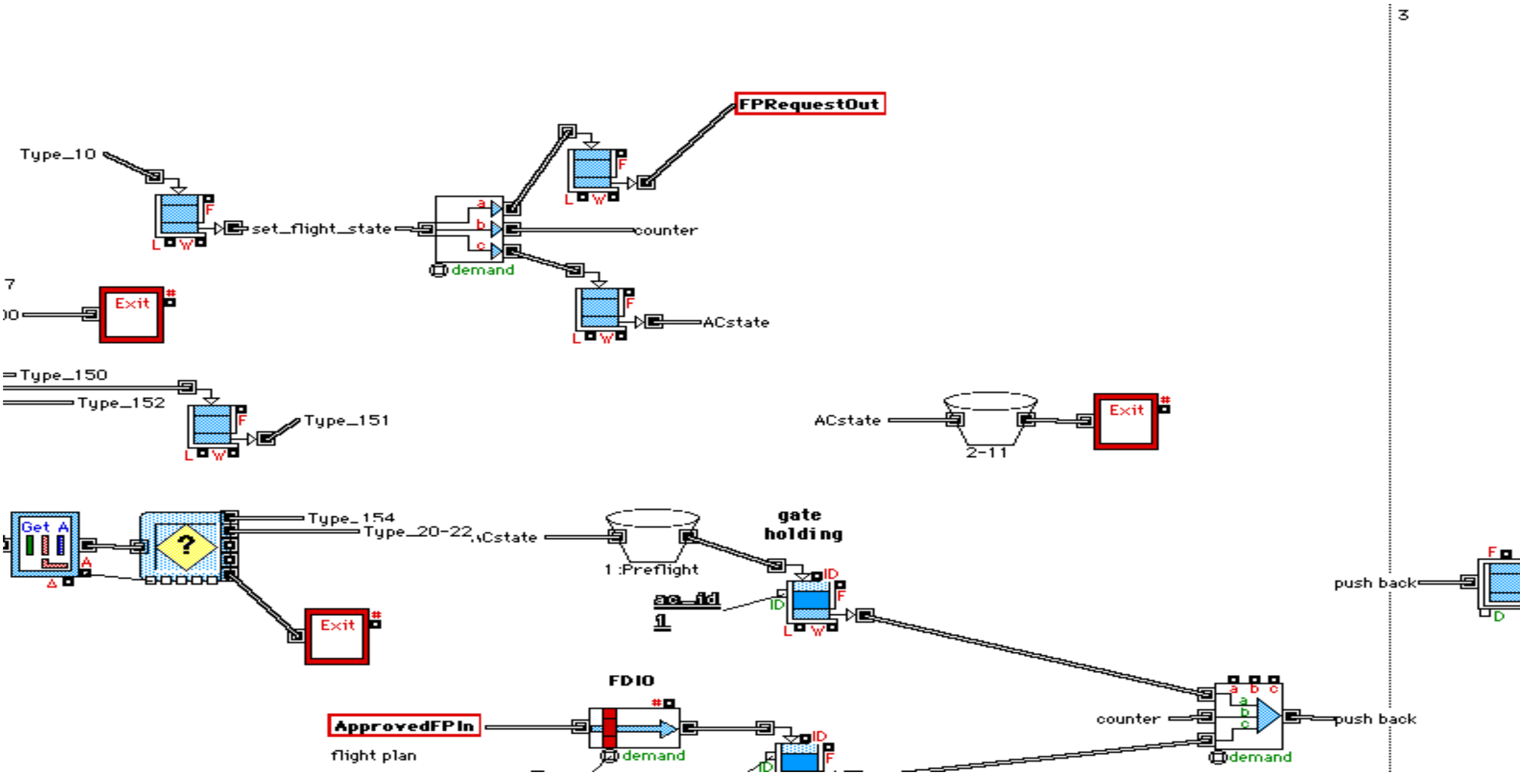

Figure 2 – Lower level view of the AC Object

Each of these trigger events causes a state change in a component of the NASSIM prototype and will cause a series of messages to flow through the model. These messages often cause other state changes and the activation of other simulation components. The Aircraft (AC) block models the communications events occurring on the flight deck of all active aircraft. The Airline Operations Center (AOC) block models the communications−related events that occur within multiple AOCs (such as the filing of a flight plan). The Communications (COMM) block functionally models all voice and Data Link channels between controllers and pilots. Similarly, the Air Traffic Control (ATC) block is used to model ATC system components including sectors, airports, TRACONs, the Host computer system, and radar sites that comprise an en route center. This NASSIM prototype model can be used to support analysis of a wide−range of alternative communication system designs and can be executed for any simulation time period.

Data Link Study

This study looked at the potential benefits from Data Link implementation. Three centers were chosen on the basis of the National Benefits Calculation (Appendix B) of "User Benefits of Two−Way Data Link ATC Communications: Aircraft Delay and Flight Efficiency in Congested En route Airspace," DOT/FAA/CT−95/4, February 1995. Atlanta Center (ZTL) was selected as the center representing highest potential benefits from Data Link implementation, with estimated annual sector losses varying between $0.5M and $15.1M. Los Angeles Center (ZLA) was selected as a representative center where the potential benefit from Data Link implementation was considered relatively average with a moderate estimated annualized sector loss for four sectors varying between $3.7M to $9.3M. Denver Center (ZDV) was selected as a representative center where the potential benefit from Data Link implementation was considered negligible. The selection of Atlanta Center also allowed comparison of the study results to those documented in DOT/FAA/CT−95/4, and the selection of ZDV permitted the inclusion of additional operational data captured by NASA under the AATT Program.

The NASSIM prototype currently supports airport operations at two airports within a modeled center; other airports within the center are modeled as traffic sources and sinks. For the Denver Center, operations at the Denver International Airport (DIA) and Colorado Springs (COS) airport were modeled. In Los Angeles Center, operations at Los Angeles International Airport (LAX) and John Wayne (SNA) airport were modeled and Atlanta Hartsfield International (ATL) and Charlotte Airport (CLT) were modeled for the Atlanta Center.

Additionally, the NASSIM prototype allows sectors to be modeled with varying levels of fidelity. A low fidelity sector simulates the events occurring during a handoff as well as aircraft generated requests for altitude, heading, and speed changes and associated controller delivered clearances. The frequency of these aircraft generated messages was based on data collection activities conducted at Denver Center as part of the NASA AATT effort.

The high fidelity sector model expands upon the low fidelity sector model by adding controller initiated traffic instructions. Since the previous en route Data Link benefits assessment was based upon detailed human−in−the−loop simulations of an arrival and a departure sector, the prototype contains high fidelity sector models for arrival and departure sectors. Sectors in the other centers were selected based on operational similarities to those Atlanta arrival and departure sectors (ZTL sectors 9 and 32).

Table 1 Scenarios Summary

	Center		
	Denver (ZDV)	Los Angeles (ZLA)	Atlanta (ZTL)
Time (local)	8:00−11:00	10:00−13:00	8:00−11:00
Airport #1	DIA	LAX	ATL
Airport #2	COS	SNA	CTL
Arrival Sector	27	19	9
Departure Sector	29	8	32

Event files for the three scenarios were generated for Wednesday, June 19, 1996. There were no adverse weather conditions on that day. There was only one national−level traffic management initiative in place, an Estimated Departure Clearance Time (EDCT) program for Newark (a traffic management initiative in which departures destined for Newark are delayed) from 1900Z to 0359Z.

Table 2 − Summary of Events

Denver Center	**DIA**	**COS**	**Other Airports**	**Total**
Arrivals	123	22	57	202
Departures	123	24	87	234
Total	246	46	144	
Sector Pierces	3552			
Total Aircraft	832			

Los Angeles Center	**LAX**	**SNA**	**Other Airports**	**Total**
Arrivals	187	36	412	635
Departures	185	32	460	677
Total	372	68	872	
Sector Pierces	3451			
Total Aircraft	1118			

Atlanta Center	**ATL**	**CLT**	**Other Airports**	**Total**
Arrivals	168	117	293	578
Departures	183	123	389	695
Total	351	240	682	

Sector Pierces	4773
Total Aircraft	1426

To match the model’s communication message frequencies to existing sectors with communications congestion, an analysis of voice communications was performed for Atlanta sectors 9 and 32. Sectors 9 and 32 experience times where controller−initiated voice communication messages in response to high traffic levels occur at frequencies high enough to result in voice communication congestion The analysis identified the types and frequencies of messages that occurred for this date. The transmissions on the tapes were broken down into two broad categories: communication messages originating from the controller, and communication messages sent to the controller. Within these two categories, the frequency of occurrence of 16 different message types was assessed.

The voice message frequencies vary sufficiently by sector type to merit computing two sets of message frequencies for controller−initiated voice communications (one for an arrival sector and one for a departure sector). Table 3 and 4 give the message frequencies.

Table 3 Arrival Sector Voice Communication Message Frequencies

Communication Event Type	**Observed Frequency**	**Decomposition Of Instruction Frequency**	
Single instruction	50.0%	# Frequency 1 26.7% 2 20.0% 3 26.7% 4 0.0% 5 13.4% 6 6.6% 7 6.6%	
Double instruction	3.3%	# Frequency 1 100.0%	
Triple instruction	0.0%	N/A	
Single and double instruction	30.0%	Single Instruction # Frequency 1 0.0% 2 14.3% 3 28.6% 4 28.6% 5 14.3% 6 0.0% 7 0.0% 8 14.2%	Double Instruction # Frequency 1 57.1% 2 28.6% 3 0.0% 4 14.3

Single and triple instruction	6.7%	Single # Frequency 1 0.0%	Triple # Frequency 1 0.0%
Double and triple instruction	0.0%	N/A	
Single, double, and triple instruction	0.0%	N/A	
No instruction	10.0%	N/A	

The data contained in this table was incorporated into the model for Atlanta sector 9, Los Angeles sector 19, and Denver sector 27.

Table 4 Departure Sector Voice Communication Message Frequencies

Communication Event Type	**Observed Frequency**	**Decomposition Of Instruction Frequency**	
Single instruction	51.8%	# Frequency 1 41.4% 2 24.1% 3 10.3% 4 3.5% 5 20.7%	
Double instruction	5.4%	# Frequency 1 100.0%	
Triple instruction	0.0%	N/A	
Single and double instruction	7.1%	Single Instruction # Frequency 1 50.0% 2 25.0% 3 25.0%	Double Instruction # Frequency 1 100.0%
Single and triple instruction	0.0%	N/A	
Double and triple instruction	0.0%	N/A	
Single, double, and triple instruction	0.0%	N/A	

No instruction	35.7%	N/A

This data was included into the representations of the departure sectors.

The analysis included 25%, 50%, 75%, and 90% Data Link equipage rates. Varying the equipage rates allows us to examine two related factors − the uncertainty in the user's propensity to equip and to evaluate Data Link impacts during a potentially lengthy transition phase. Since a Free Flight tenet is no mandates, this provides an analysis of the sensitivity of benefits to that principle. The baseline analysis used a 0% equipage rate corresponding to current operations.

The analysis included an assessment of the impact of different concepts of operation involving Data Link implementation by comparing two Data Link message sets against the baseline. The first set, Message Set A, included the transfer of communications and initial contact messages being sent and received via Data Link for equipped aircraft. The second set, Message Set B, expanded upon the first by adding altitude, speed, and heading clearances, and acknowledgments.

Voice communication times were obtained from "Validation of Air Traffic Controller Workload Models" FAA−RD−79−83, September 1979. Data link communications times were derived from data contained in the "Minimum Operational Performance Standards For Two−Way Data Link Communications" RTCA DO−219, August 1993 and from TDMA Data Link performance parameters. For the purposes of this analysis the performance characteristics of TDMA Data Link were used.

For the purposes of this analysis, we assumed that a transfer of communication and subsequent initial contact message would be associated with each sector pierce. We also assumed that a heading, speed, or altitude clearance would be issued once per sector. These assumption were based upon interviews conducted at the Denver ARTCC (ZDV) as part of the previously mentioned NASA AATT study. For the higher fidelity sectors, controller−initiated instructions were issued according to the message frequencies in Tables 3 and 4.

The following metrics were used in assessing the impact of Data Link implementation:

> **Communications Utilization** The percentage of time the voice frequency was in use. Utilization was computed by dividing the time in use by the total scenario time.
>
> **Channel Occupancy** The number of minutes that a voice channel was in use during the scenario.
>
> **Total Message Delay** The total number of minutes voice communication messages were delayed. Total message delay was computed by multiplying the average message latency by the number of messages.

Figures 3 and 4 compare communication utilization rates for Message Sets A and B for the three centers (Denver, Los Angeles, and Atlanta). These figures illustrate that, based upon the message frequencies selected for this study, communications utilization reductions achieved through Data Link implementation were uniform between centers. The baseline utilization for the three centers varies from 10.9% to 11.9% and is reduced to approximately 4% for all three centers for Message Set A operating at a 90% equipage rate. Of the 18489 communication messages observed in the Denver scenario, 12814 (i.e. 69%) were associated with handoff events. Similarly, the Los Angeles scenario contained 16751 communication messages of which 11984 (i.e. 72%) were associated with handoff events. The Atlanta scenario contained the highest number of communication messages 23220, of which 16864 (i.e. 73%) were associated with handoffs. Since the majority of messages in these scenarios were included in Message Set A, it is reasonable to expect reductions in communications utilization between centers to be uniformly distributed. While the Atlanta center contains the highest communications utilization, it also has the largest number of sectors, 45. The Denver and Los Angeles centers have a slightly lower number of sectors, 39 and 35 respectively. Factors such as average sector occupancy time and traffic levels also impact communications utilization.

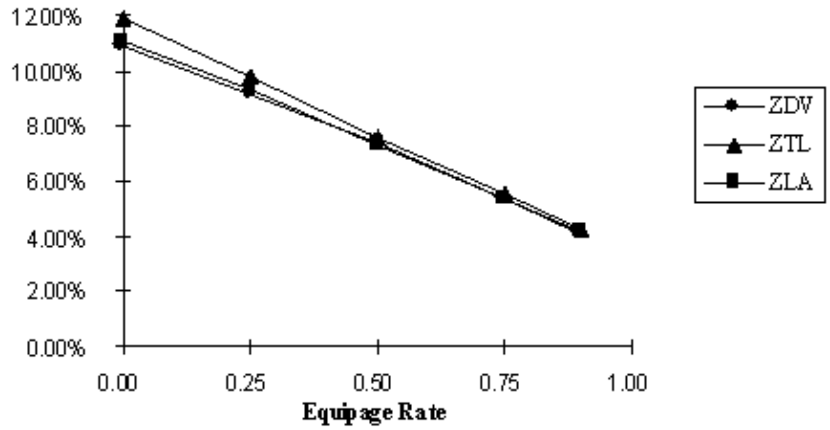

Figure 3. Communication Utilization Comparison (Message Set A)

In Message Set B, all messages transmitted between the aircraft and the controller are sent via Data Link if the aircraft is so equipped. Figure 4 shows an even higher reduction in communications utilization (to approximately 1%) for the 90% equipage rate. As with Message Set A, the reductions in communication utilization were consistent between centers.

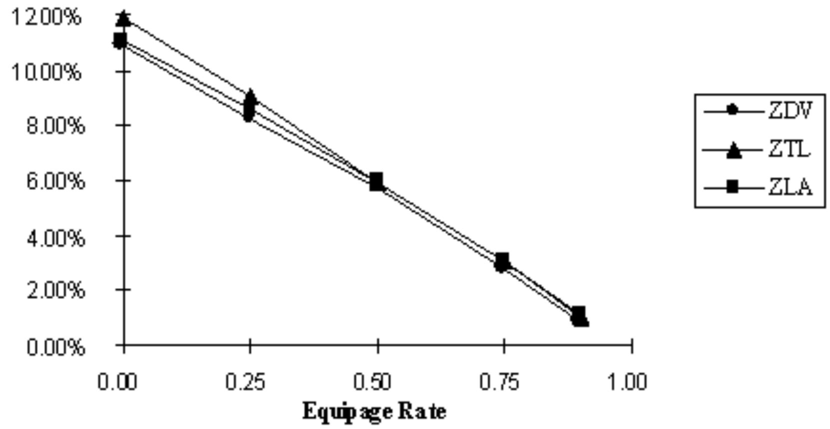

Figure 4. Communication Utilization Comparison (Message Set B)

Figures 5 and 6 compare voice channel occupancy for Message Sets A and B for the three centers. The largest contributors, in this study, to communications utilization and voice channel occupancy were communications events associated with handoffs. Both figures illustrate Atlanta Center as having the highest voice channel occupancy, followed by Denver Center, with Los Angeles Center following a close third. Since the Atlanta scenario has the most sectors and the Denver and Los Angeles scenarios contained approximately the same number of sector pierces, the results are very reasonable.

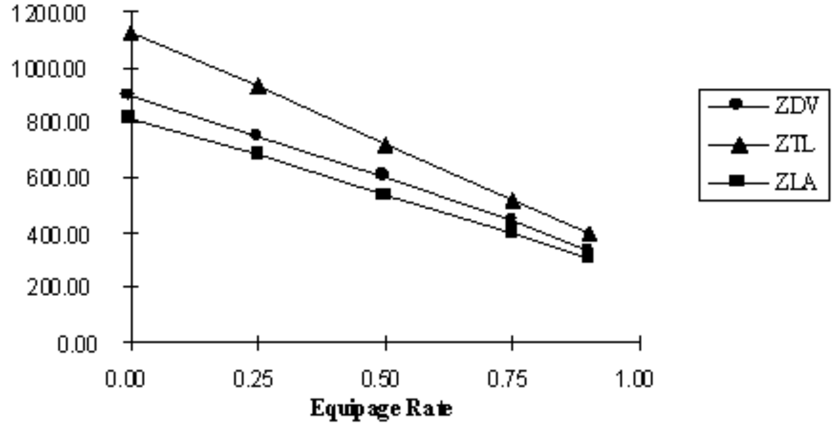

Figure 5. Voice Channel Occupancy Comparison (Message Set A)

Figure 6 illustrates further reductions in voice channel occupancy for Message Set B with approximately 100 minutes for each of the three centers.

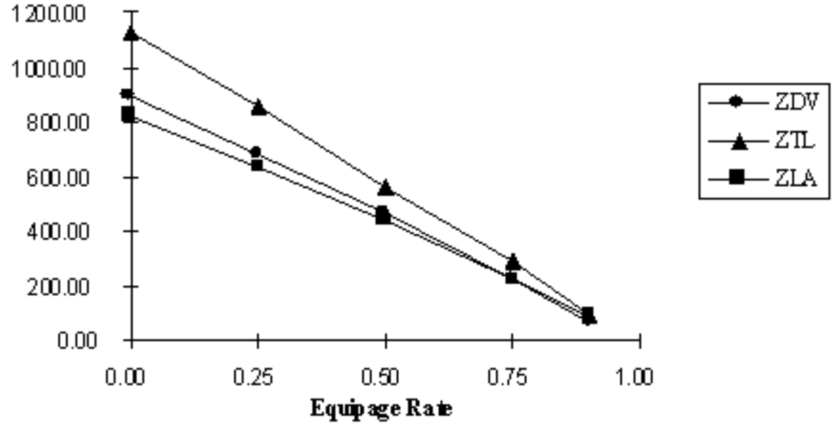

Figure 6. Voice Channel Occupancy Comparison (Message Set B)

While voice channel occupancy and communications utilization are both nearly linearly related with Data Link equipage rate, the total message delay associated with Message Set B is not, as illustrated by the data contained in Table 5. These results indicate that even at low equipage rates (such as 25%) there is a significant reduction in total measured message delay, which is again consistent between centers. Thus, while higher Data Link equipage rates provide greater benefits, this metric provides an indication of the timeliness with which messages are exchanged between pilot and controller would show a significant improvement even with low equipage rates.

Table 5 Total Message Delay Reduction

Equipage Rate	Denver		Los Angeles		Atlanta	
	Total Message Delay (min)	Reduction From Baseline (%)	Total Message Delay (min)	Reduction From Baseline (%)	Total Message Delay (min)	Reduction From Baseline (%)
0	67.8	N/A	44.3	N/A	61.3	N/A
25	37.6	44.5	25.8	41.8	34.6	43.6
50	16.5	75.7	12.7	71.3	16.9	72.4
75	5.8	91.4	3.7	91.6	4.9	92.0
90	0.7	99.0	1.3	97.1	0.9	98 .5

Thus this study indicates that the use of Data Link for en route communications can reduce existing voice channel utilization, voice channel occupancies, and total message delays. These reductions were achieved for all three centers evaluated, both of the Data Link message sets, and all equipage rates (25%, 50%, 75%, and 90%) used in this study. Voice communications utilization and voice channel occupancy reductions were observed to be consistent between the three centers. Total message delay reductions were observed to be non−linear for each of the three centers. This result is attributable to the fact that this metric measures voice channel contention. The study results show that even low equipage rates result in significant reductions in voice message delay. For example, the results of the study indicate that a 25% Data Link equipage rate can reduce total message delays by as much as one−half.

One of the past arguments regarding Data Link has been that users might be slow to equip due to a perceived lack of benefits and thus the transition period may be quite lengthy. However, based upon the total message delay metric, even at low equipage rates Data Link provides significant benefit.

Next Step for Data link Analysis

The previous results are due in part to the message rates used in the simulation which were based upon an analysis of voice tapes for two sectors (9 and 32) within Atlanta Center. To provide more confidence in NASSIM output, the variance in message rates across sectors by type (such as high, low, transition) requires further analysis. This analysis would require an extension of the voice tape analysis previously performed but could also address the frequency of miscommunications under voice operations. Since reduction in miscommunications has been identified as one of the potential benefits of data link this data could be used to enhance NASSIM to include miscommunications events.

The NASSIM study recently completed includes total message delay as a performance metric. While this metric provides an indication of the amount of contention that occurs for the voice frequency, the resultant operational impacts could be better assessed if NASSIM included message priorities (to enable analyzing the number of critical messages delayed).

One of the objectives of the multi−Center NASSIM study was to assess the impacts of various data link equipage rates since it is difficult to predict what the ultimate, final equipage rate will be and the transition phase to this end−state might be quite lengthy. The study indicated that for data link equipage rates as high as 90 percent the two alternative ATC message sets incurred no measurable delay when TDMA data link performance characteristics were assumed. There are however, numerous proposals to expand data link services to other message set such as graphical weather and traffic information service as an incentive for users to equip with data link. The impacts of these additional services on data link performance should be analyzed for TDMA and other candidate data link alternatives to determine whether this is a supportable option.

Next Steps

There are other significant questions to be addressed in the above analyses, and in the future, with respect to how changes in operational concepts impact human performance. The data link analysis showed how data gathered in simulations can be used to modify and evaluate the performance changes in a full center context through NASSIM modeling. An investigation of the capability of the controller to operate data link in a mixed equipped environment needs to be conducted to validate assumptions and then rolled back into the model.

This tie between human performance simulation and modeling is a process that needs to be formalized as we move to concept validations for the mid and far term Global Airspace System. We are investigating, as part of the work we do in the joint FAA/NASA IPT, how to use the capabilities that the MIDAS model for instance, to extend NASSIM to future concepts. The results of MIDAS analyses can be included as distributions of behaviors for the controller and pilot components. The components are triggered by events consistent with future operational events and can extend (in a simplified fashion) MIDAS results into a center/multi−center simulation with multiple traffic mixes to look at information loads on both the human and technological components of the National Airspace System.