IMPACTS OF A MIXED MEDIA AIR TRAFFIC CONTROL COMMUNICATION ENVIRONMENT ON AVIATION EFFICIENCY

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Abstract

As the number of aircraft in a sector increases, voice channel usage also increases. As a result, air traffic controllers experience a workload increase; this larger workload leads to an increase in distances flown by potentially conflicting aircraft. Flight plan deviations, in addition to further increasing controller workload, also increase inefficiencies in the air traffic system. To reduce the voice usage, the use of a mixed media voice and datalink system has been proposed. It is postulated that by reducing voice usage, controller workload and, by extension, the inefficiencies in the system, will be decreased.

This study develops a controller workload model for a voice-only and a mixed-media environment. Enroute air traffic control communication data are used as empirical inputs to determine qualitative values for controller workload, and these values are correlated with vector deviations from assigned flight paths to determine the degree of inefficiencies associated with the workload. This research demonstrates increased efficiency with the use of a mixed-media environment, as increasing efficiency in the air traffic system would have wide reaching impacts in many aspects of the aviation community, including economic, environmental, and customer service arenas.

Keywords: datalink, NextGen, air traffic control, workload, cognitive utilization

Introduction

Currently, the National Airspace System (NAS) is experiencing severe capacity constraints. These constraints manifest themselves in delays and other forms of inefficiencies in the air traffic control environment. Many of these capacity constraints are due to an increase in air traffic. As air traffic in a sector increases, so does the use of the radio frequency associated with that sector.

More traffic and less available radio frequency time translate to a higher workload for a sector's controller. When controllers encounter potential conflicts during a period of high workload, greater distances may be assigned to ensure separation, or controllers may, due to workload, be unable to re-vector aircraft as quickly as they would during periods of lesser workload. The introduction of the Next Generation Air Transportation System (NextGen) has potential to decrease controller workload through the introduction of data communications enhancements. These data communications enhancements will remove selected pilot-controller communications from the voice frequencies to a text-based data transfer environment known as datalink (1).

The introduction of datalink to the ATC system will occur in stages. The first stage, Segment 1, includes four dimensional trajectory management, communications management, enroute clearances, and ground-issued clearances and taxi instructions. This segment aims to provide these services to en route and tower flight control environments. Segment 2 increases the data communications capabilities somewhat, by adding further 4D trajectory agreements, enroute 4D trajectory clearances, and information on status, delay, and constraints within the NAS. Segment 2 also is concerned with expanding the use of Segment 1's services to include terminal control areas. Segment 3, which does not affect this study, expands the use of data communications technologies to widespread 4D trajectory use, widespread separation minimums, and zero-visibility taxi guidance (2; 3).

In this study, the main concern is the use of data communications during enroute phases of flight. The majority of communications that this study addresses are dealt with during Segment 1.

Communication types that are deemed non-critical for this case are handoffs, check-ins, altimeter readings, and speed, altitude, heading, and route clearances, as well as the appropriate responses to these communications.

Previous studies investigating the use of datalink in the ATC environment have demonstrated that datalink message transfer times are greater than the transfer times related to voice communications. These longer times are due to delays in message communication caused by technological limitations; however, as datalink becomes more widely used in the ATC environment, further advances in data transfer times will be developed and the latency issues associated with datalink will be lessened (3). Another factor in datalink's lengthier communication times is the time required for message composition. Composition in a text-based environment requires more time because of the message's manual entry.

However, the increased transmission time for datalink communications does not pose a significant problem for ATC communications. In Segment 1, messages sent via datalink will be non-critical messages, so time is not a crucial part of these communications. By sending these non-critical messages over datalink, the voice frequencies will be more available to deal with more crucial communications. Additionally, a portion of the messages sent via datalink are routine communications such as handoffs and check-ins. Controllers' messages associated with these routine events may be automated, allowing them to merely press a button to acknowledge or send a message, thus reducing the time spent in message composition.

The significance of this work is in providing an indication of benefits that can be gained by implementing the use of data communications in the air traffic control environment. A decrease in the workload of en route air traffic controllers could lead to a decrease in controller-assigned deviations from flight paths, leading to an increase in aspects of the air traffic control system.

Methodology

The proposed methodology for this study takes the following steps: 1) determine inputs for a voice-only workload model; 2) determine a relationship between voice-only data and mixed-media data; 3) formulate a relationship between selected inputs and the vector distances flown; and 4) calculate potential reductions in controller workload and vector distances assigned for a mixed-media environment.

Study data

In this study, a voice communications database of recordings obtained from MITRE and the Federal Aviation Administration (FAA) Technical Center was analyzed. Ten super-high and high-altitude en route sectors from Indianapolis Air Route Traffic Control Center (ZID) yielded twelve controller-pilot voice communications recordings. Eleven of these samples were thirty minute samples; the last sample was four hours and sixteen minutes. These recordings provided a total of nearly ten hours of data. The selected sectors represent a wide variety in sector size, complexity, flight levels, and demand levels.

The communications in this database had previously been analyzed to isolate incidents where aircraft were vectored due to conflicting traffic. The filed route and the vector distances assigned to each deviated aircraft were obtained from XEval. XEval is a model for aircraft traffic and conflict analysis that uses data from air traffic decision support tools such as the User Request Evaluation Tool (URET) to provide data on an aircraft's planned route and the route actually flown. The difference between the distance of the filed route and the route actually flown is termed "excess distance."

Workload inputs

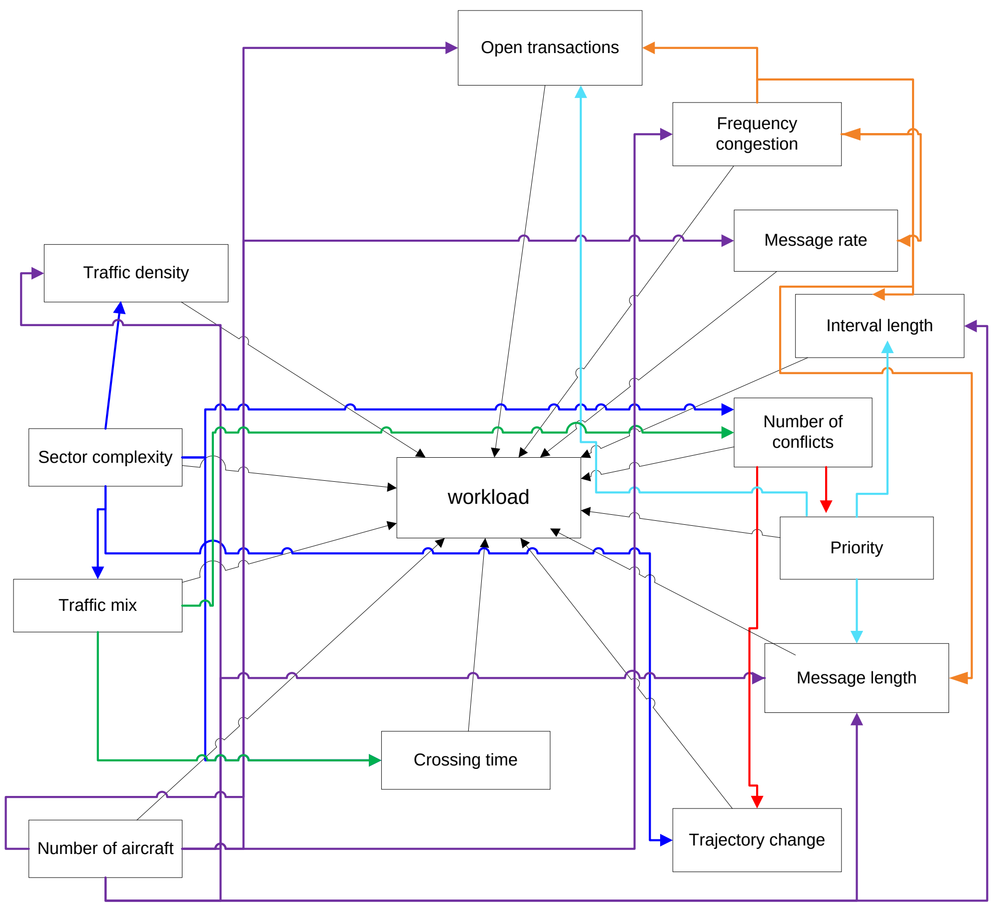
Workload metrics and models investigated in this study revealed a list of factors contributing to controller workload. A complete summary of the relevant factors is listed in Table 1.

An analysis of the input variables reveals a number of interdependencies between the inputs, and also allows the substitution of some inputs for others. A flowchart, shown in Figure 1, demonstrates the interactions of each parameter. The flowchart, paired with an analysis of the input variables, shows that there are interdependencies between trajectories and number of conflicts, message rates and frequency congestion, message length and frequency congestion, and priority and number of conflicts. These interdependencies allow variables to be substituted for one another.

Factor	Description
Message length	Time from beginning to end of message
Trajectory	Change in aircraft heading, altitude, or speed
Crossing time	Time required for aircraft to cross a sector
Traffic density	Number of aircraft per sector area
Message rate	Rate at which messages arrive and depart
Open transactions	Number of open transactions at a given point in time
Interval length	Time from end of a sent message to beginning of received message
Priority	Importance of an open transaction
Sector complexity	Sector difficulty due to size, flows, flow interactions, etc.
Frequency congestion	Percentage of radio channel time used
Number of conflicts	Number of potential conflicts at a given point in time
Traffic mix	Distribution of aircraft types in a sector
Number of aircraft	Number of aircraft in a sector at a given point in time

Table 1: Input variables

Figure 1: Workload input interdependencies



Since the number of inputs is large, a more manageable set of workload inputs was developed. By utilizing the inputs' interdependencies and using substitution to replace the input variables for trajectory,

message rate, message and interval length, priority, frequency congestion, number of conflicts, and traffic mix, the workload model becomes
W = f(sector complexity, number of aircraft, frequency congestion).

Cognitive utilization

Previous work done by Bolic, Rakas, and Yang (4; 5) introduced the concept of the open transaction. A transaction includes all messages exchanged between a pilot and a controller before the issues raised in that exchange are concluded. Table 2 provides an example of a complete transaction. During the time that a transaction is unresolved, it is referred to as an "open transaction." Since transactions may consist of multiple messages, it is possible to have transactions nested within open transactions.

Time	Callsign	Speaker	Text
22:58:52	N349JC	Controller	november 3 4 9 juliet charlie descend and maintain flight level 2 8 0
22:58:58	N349JC	Pilot	down to 2 8 0 for juliet charlie
22:59:20	N349JC	Controller	november juliet charlie if you would hold at least 15 hundred foot rate of descend through flight level 2 9 0
22:59:28	N349JC	Pilot	ok 15 hundred feet a minute through 2 9 0 for juliet charlie

Table 2: Example of a complete transaction

The use of the open transaction concept allows for elaboration on the metric of total time on frequency, which is a commonly used workload metric. A metric defined by Bolic, Rakas, and Hansen, called "cognitive utilization," is based on the number of open transactions and accounts for the amount of time during which a controller must be aware of an aircraft.

Cognitive utilization can be related to the inputs influencing controller workload. It is based on the number of open transactions that occur during a given time period. As indicated from Figure 1, open transactions are a function of priority, frequency congestion, and number of aircraft. Given the previous definition of the workload model, this allows cognitive utilization to be directly substituted into the workload model.

To determine cognitive utilization, each data set was segmented into five-minute bins. The duration of each interval in which at least one transaction was open was multiplied by the number of open transactions in that interval. The resulting values were summed over each bin to establish the time spent thinking about each aircraft; this sum was then divided by the bin length to calculate the percentage of time a controller needed to be aware of the aircraft in the sector. Thus, workload is defined as
W = f(sector complexity, cognitive utilization, number of aircraft).

Sector complexity and monitor alert parameter

Studies and investigations of controller workload have used a number of metrics to measure workload levels. These metrics range from simple and static, such as the monitor alert parameter (MAP) and time spent on frequency, to complex and dynamic, such as dynamic density.

Dynamic density is a proposed metric that measures both traffic density and complexity within a sector. In previous research, it has been suggested that a metric that captures both density and complexity will provide a better indication of a controller's workload than metrics that only account for density (6). In this study, dynamic density is represented by a combination of sector complexity and MAP.

A basic representation of sector complexity can be constructed from sector size, the number of entry and exit points into a sector, and the number of crossing points within the sector. These parameters capture the physical characteristics of a sector.

For this study, sector complexity was calculated by determining the number of points per area of a sector. The points in question refer to the sum of the crossing points and the entry and exit points. These points were determined by displaying each sector using NASA's Future ATM Concepts Evaluation Tool (FACET), and overlaying it with jet airways. The points at which the airways intersected the sector perimeter were counted as entry and exit points, while the points at which the airways crossed within the sector were counted as crossing points. Area was calculated by taking the product of the length of the widest point of each sector in either direction. This method of determining sector complexity is a simplification, and thus it provides only a certain aspect of this variable.

A sector's MAP value is an indication of how many aircraft can be adequately handled within that sector for a 15-minute period. Though the MAP value by itself may not provide a sufficient measure of a sector's difficulty (7), when paired with a measure of physical sector complexity, it is able to provide an adequate representation of sector complexity. MAP values were obtained from FACET.

Datalink workload inputs

This study addresses the use of datalink as a tool to reduce air traffic controller workload. To accomplish this, datalink input data must be used as an input to the workload model. A particular challenge in this study is that actual mixed media pilot-controller communications data was unable to be obtained. Thus, it was necessary to transform the existing voice-only data into a representation of mixed-media data.

Sector complexity and MAP

Sector complexity and MAP, as discussed above, are based on the physical characteristics of a sector and an assessment of the sector's difficulty. As long as the ambient conditions, such as weather, equipment, and controller experience, in a sector remain the same, it can be said that these factors do not change when transitioning from a voice-only to a mixed-media environment.

Cognitive utilization

In addition to freeing up radio frequency capacity, moving specific communications to the datalink channel has implications for shifting controller workloads from mainly an aural mode to a combination of aural/verbal and visual/manual modes. Research has indicated that workload reductions may occur through the use of two or more modes, provided that these modes do not interfere with each other (8; 9). Simultaneously processing aural and visual information presents little difficulty, as it is thought that the visual and aural systems do not share the same space in memory (9).

Wickens' model of multiple resource theory states that concurrently performing time-shared tasks causes a reduction in task performance in relation to the performance that would occur if each task was executed separately (10). This model is developed by calculating the total demand required for a task pair, then multiplying them by an interference value determined from a conflict matrix to give the total cognitive interference for the pair (11). In this case, the tasks will be voice communication and datalink communication, and the demand used will be cognitive utilization.

Datalink Cognitive Utilization

In transforming the voice-only data to a representation of mixed-media data, the data was analyzed to determine which messages could be sent via datalink, and the resulting data subset was tagged to identify it for later use.

To approximate the transaction time required to send and receive a datalink message, one-way latency time was considered. In Segment 1, the maximum latency time is 8 seconds (3). Message reading time and composition time were adjusted by dividing the number of words in a message by the average silent reading rate or average typing speed, respectively. Average silent reading rate is approximately 5 words per second, and the average typing speed is about 0.58 words per second (12).

However, some messages are so simple and routine that they are good candidates for automation. These messages, such as hand-offs and check-ins, were isolated and assigned total transmission times of

8.5 seconds. This time accounts for the latency time and an estimate of the time required for a controller to find and press a single response key.

The cognitive processing time required to plan a response to a received datalink message is assumed to be the same as the time required for a message received via voice.

The application of these transformations increases the communication times for some messages and decreases them for others, and thus changes the bin lengths. To account for this, corrected intervals for datalink and voice communications and the communication intervals that were not part of open transactions were summed up for each original five-minute interval, resulting in a new total time for each bin. The bin's total usage was then divided by the corrected bin time to determine the datalink cognitive utilization.

Voice Cognitive Utilization

Voice cognitive utilization in the mixed-media environment was obtained by determining which communications would still be transmitted via radio. Once this was determined, the corrected intervals from the voice-only environment for these communications were summed to calculate the new total voice cognitive usage for each bin. The recalculated bin times were used to determine the total voice cognitive utilization for the mixed-media environment.

Table 3 provides a list of the transformation equations used to develop this representation of the mixed-media communications environment.

Media type	***Issued by***	***Cognition***	***Transformation***
Datalink	Pilot	Comprehension	$8\,s + \frac{number\ of\ words}{average\ reading\ rate}$
Datalink	None	Planning	No transformation
Datalink	Controller	Composition, non-automated	$8\,s + \frac{number\ of\ words}{average\ typing\ speed}$
Datalink	Controller	Composition, automated	$8.5\,s$
Voice	Pilot None Controller	Comprehension Planning Composition	No transformation

Table 3: Mixed-media transformation equations

Mixed Media Cognitive Utilization

Calculation of the cognitive utilization for the mixed-media environment was based on North and Riley's workload index (W/INDEX) model, which is strongly based on Wickens' model for multiple resource theory (11; 10). The voice and the datalink cognitive utilization values were added together to obtain the total cognitive demand on the controller at the point of the conflict.

The matrix in Table 4 provides conflict values for all possible combinations of voice and datalink message pairs.

			Task A			
			Voice		Datalink	
			Perception/ cognition	*Response*	*Perception/ cognition*	*Response*
Task B	Voice	*Perception/ cognition*	0.8	0.6	0.6	0.4
		Response	0.6	1.0	0.4	0.6
	Datalink	*Perception/ cognition*	0.6	0.6	0.8	0.6
		Response	0.4	0.6	0.6	0.8

Table 4: Cognitive conflict matrix for task pairs, x_{ab} (source: Wickens, 2002)

As the matrix shows, there are a number of possible combinations of message pairs with which a controller may be confronted. Rather than analyze the entire dataset and assign discrete conflict values for each message based on the previously received message, this study uses message probability to determine an average conflict value for the mixed media environment.

An analysis of all messages in the dataset found that, overall, 45.3% of the messages are candidates to be moved to datalink in Segment 1. Additionally, in a study by Rakas, Hansen, Jirajaruporn, and Bolic, the number of pilot communications and the number of controller communications was found to be nearly equal (13). Thus, 22.6% of the messages were sent via datalink, and 27.4% of the messages were sent via voice. The same distribution of messages was received via datalink and voice, respectively.

The cognitive conflict matrix presented in Table 4 provides conflict values for message pairs. The probabilities of receiving each message pair was calculated by multiplying the individual probabilities for each component of the pair. Table 5 provides a complete listing of the probabilities for each type of message pair.

			Task A			
			Voice		Datalink	
			Perception/ cognition	*Response*	*Perception/ cognition*	*Response*
Task B	Voice	*Perception/ cognition*	0.074	0.074	0.062	0.062
		Response	0.074	0.074	0.062	0.062
	Datalink	*Perception/ cognition*	0.062	0.062	0.052	0.052
		Response	0.062	0.062	0.052	0.052

Table 5: Probability of message type pairs, p_{ab}

The expected conflict value for all messages was determined by computing the average of the conflict value for each message pair type, weighted by the probability of the occurrence of each message pair, as shown in Equation 1. The resulting expected conflict value $x_{conflict}$ for all messages was calculated as 0.616.

$$x_{conflict} = \sum_{a,b} x_{ab} p_{ab} \qquad \textbf{Eq. 1}$$

A similar calculation was performed to determine the expected conflict value for the voice-only situation. This conflict value was calculated as 0.75. From here, it can be seen that a workload reduction is incurred by introducing datalink to the air traffic control environment. The percentage of a controller's workload that remains after this introduction, referred to as the ratio *r*, is given in Equation 2 as

$$r = \frac{x_{conflict_{mixed}}}{x_{conflict_{voice}}}$$ **Eq. 2**

This remaining workload was calculated as 0.821; the total cognitive demand was multiplied by this value, resulting in the mixed-media cognitive utilization value $u_{mixed\ media}$, as shown in Equation 3.

$$u_{mixed\ media} = r(u_{voice} + u_{datalink})$$ **Eq. 3**

Workload model

The relationship between the excess vector distances flown and the workload inputs was determined through the use of linear regression. The excess vector distance was the dependent variable in the regression, while cognitive utilization, sector complexity, MAP, and aircraft count were potential explanatory variables.

A stepwise R^2 regression was first run to determine the effects of each explanatory variable. The coefficients for cognitive utilization were positive and were consistent through each step. This demonstrates not only a strong positive relationship between excess vector distances and cognitive utilization, but also indicates that cognitive utilization is not being influenced by the addition of further variables. Table 6 lists the coefficients for each iteration; the cognitive utilization coefficients are shown in bold italics.

Iteration	***Explanatory Variable***	***Coefficient***
1	Cognitive utilization	***4.40***
2	Cognitive utilization	***4.52***
2	Sector complexity	-1571.53
3	Cognitive utilization	***4.56***
3	Sector complexity	-1313.63
3	MAP	0.26
4	Cognitive utilization	***4.14***
4	Sector complexity	-1387.95
4	Aircraft count	0.11
4	MAP	0.25

Table 6: Stepwise R-square regression coefficients

Model interpretation in a conventional communication environment

The final regression for a three-variable model results in a relationship between excess distance, cognitive utilization, sector complexity, and MAP, as shown in Equation 4.

$$d = -1.06 + 4.558u - 1313.628c + 0.262m$$ **Eq. 4**

where $d = \text{excess dist}$
$u = \text{cognitive utilization}$
$c = \text{sector complexity}$
$m = \text{MAP}$

A three-variable model was used for the final model instead of the expected four-variable model, because additional regressions demonstrated that the variable for number of aircraft did not contribute significantly enough to the model. This model predicts about 30% of the variation found in the excess distance data. Though the predictive capabilities of this model are somewhat low, a positive relationship between cognitive utilization and the magnitude of excess distances is indicated. Additionally, this study does not account for complex factors, such as weather, airspace usage, and variations in human behavior. These factors have the potential to account for a significant amount of variation in excess distance data.

The signs of the coefficients are mostly what are expected. Cognitive utilization has a significant effect on excess distances flown by aircraft, indicating that it is the primary driver for the magnitude of the dependent variable. However, the sign associated with the sector complexity coefficient is surprising. A possible explanation for this result is that a sector with a high sector complexity rating requires greater vigilance on the part of the controller. Such a sector is likely to have a higher concentration of conflict points; because of this, the controller has less space in which to resolve conflicts.

Figure 2 shows an example of the same sector with differing complexity. The large number of flows and crossing points in the first example leaves very little room for a controller to vector conflicting aircraft. The second example shows a much lower sector complexity, and in comparison, allows for the use of greater vector distances.

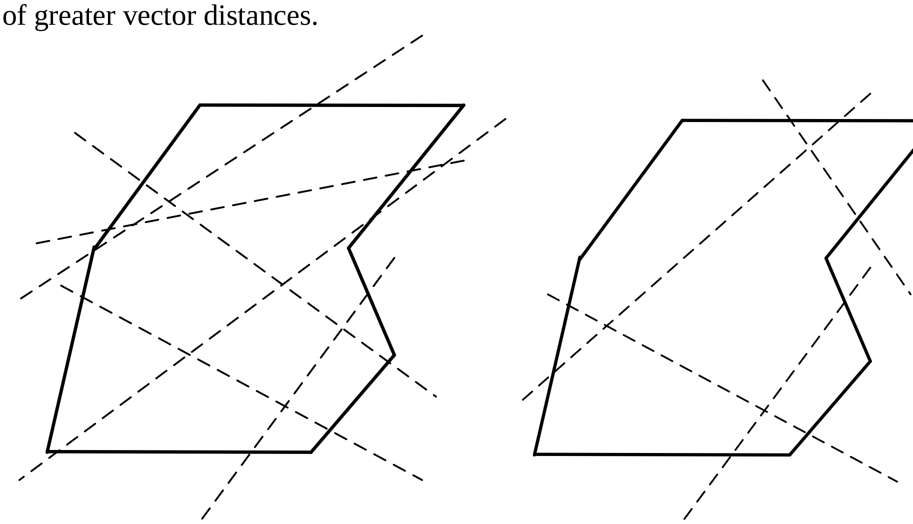


Figure 2: High vs. low sector complexity

Model interpretation in a mixed-media communication environment

The simulated mixed-media data, when applied to the excess distance model, resulted in a slight overall reduction in the predicted excess distances. After accounting for outliers in the data, Reduction in excess distance shows the mean distances for voice and mixed-media environments, and the reduction associated with the use of datalink.

		Mean (nm)	***Reduction (nm)***	***σ***
Media	Voice-only, actual	3.581	0.02	2.427
	Mixed-media, predicted	3.561	0	1.375

Table 7: Reduction in excess distance

On an individual basis, the excess distance model predicted reductions from actual data for approximately 40% of the data points. The model predicted a mean reduction of 1.826 nm for twenty-one cases, and a mean increase of 1.288 nm for the remaining thirty cases. Figure 3 shows the predicted change in excess distances for actual voice data versus predicted mixed-media data.

The low percentage of reductions in excess distance is due to the assumption of the worst-case scenario for datalink latency. As mentioned previously, the 8-second one-way latency value is the maximum allowable latency time, as required in NextGen's Segment 1. However, the objective latency time in Segment 1 is 3 seconds; in Segments 2 and 3, the maximum latency time is 3 seconds and the objective is 1.5 seconds (3). Because this study assumes the worst-case latency, the number of predicted reductions is artificially low.

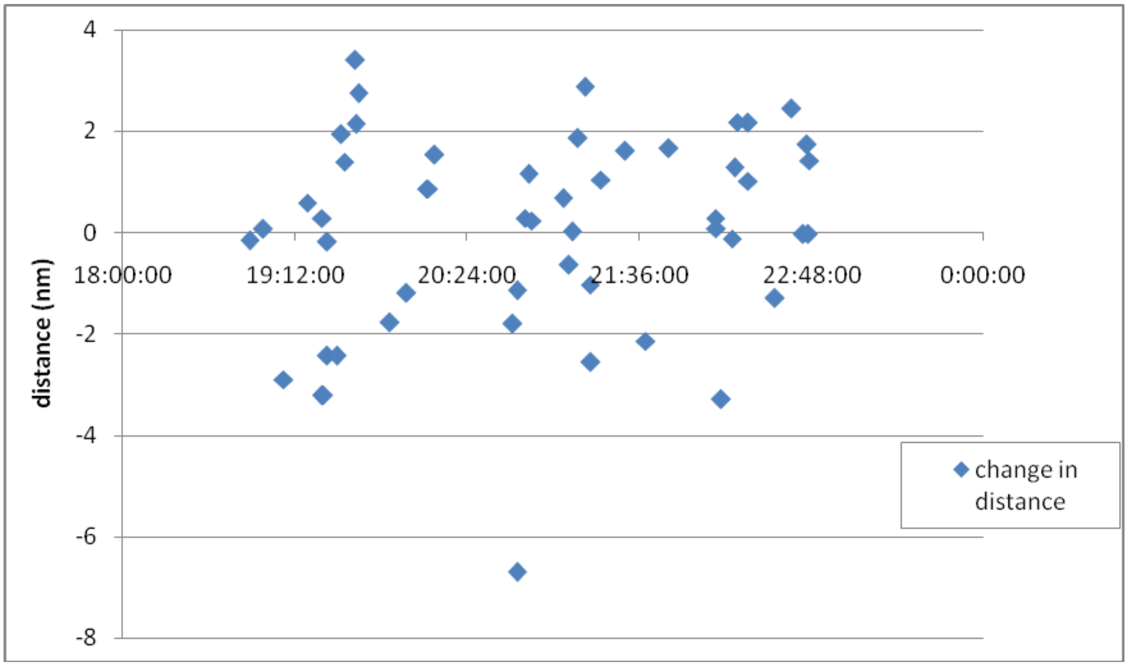


Figure 3: Excess distance errors

Discussion and Conclusions

This study explores the impact of the use of a mixed-media environment on excess distances flown by aircraft. According to the results, the introduction of datalink to the air traffic control environment has the potential to reduce the excess distance flown by aircraft as a result of a deviation by air traffic control by about 0.02 nm per deviation. Though this reduction is small, if an aircraft deviates from its path multiple times per flight, these reductions add up; similarly, the reductions also accumulate throughout the air traffic system, and have implications on fuel usage and environmental conservation, as well as airline profitability.

These results have at their core a conservative estimate of datalink transmission time; an extension of this study is recommended to examine how changes in datalink performance may affect changes in excess distance.

Additionally, this work looks at the effects of multiple tasks performed in multiple modes, and their effects on workload. The treatment of these concepts is an initial look at how a controller performs when confronted with a bimodal air traffic control environment, and examines only the effects on communications. It does not look at how a controller might interact with the communications environment and with retaining and updating the mental model of a control situation, nor does it account for control tasks that are in various stages of planning or processing. A closer examination of these relationships is recommended in future studies.

This study also develops a model that demonstrates a positive relationship between excess distances and controller cognitive utilization. This model does not account for complex factors such as weather or equipment, and future work is recommended to extend this model to include such factors.

Finally, it is recommended that further research on the use of a mixed-media environment be conducted using actual human subjects and a real mixed-media environment to investigate the plausibility of the assumptions and estimations in this study, and to also investigate how the conclusions drawn here stand up to an actual mixed-media situation.

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