CONTROLLER-PILOT RADIO CHANNEL UTILIZATION AND COGNITIVE ISSUES

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Abstract

This paper introduces a new metric, termed cognitive utilization, which tries to capture the percentage of time in which a controller has to "think" about certain aircraft. In that sense, cognitive utilization sums all the time intervals during which a specific communication "transaction" is underway. Voice-communication messages for fifteen 30-minute sector samples, and traffic count data are analyzed in order to determine whether cognitive utilization affects sector capacity. First, we investigate the relation between physical radio channel utilization and sector capacity, and then, whether there is an independent cognitive effect.

We find that in most cases cognitive and physical utilization are closely correlated, but that there are a few instances in which the former vastly exceeds the latter. It appears that when this occurs, controllers' and pilots' capacity to conduct voice communications is substantially reduced.

Introduction

The constraints of voice-based communication on the air traffic control system and benefits of switching to data link communication are topics of continued interest to aviation researchers and policy makers. It is widely accepted that voice communication is an important source of workload in the current system. A high correlation (.88) between time spent communicating and a controller's subjective assessment of workload has been found in [1].

Other research reports that subjective workload assessments by subject matter experts can be better explained by a combination of traffic and communication variables than by traffic variables alone [2].

The importance of voice communication activity as a workload driver leads naturally to the question of what metrics best capture the amount of communications activity and the impact of that activity on workload. Metrics including time spent communicating, number of communication events, and number of communication events by category (advisory, instructional, etc) have been employed for this purpose in [2]. Earlier work has also focused on the number of communications [3], or the amount of communication time, as in [1] and [4]. Several other communications metrics are considered in [5], including the number and duration of pauses, the number of restarts (indicating a mistake in an initial message), the number of topics, and the number of syllables enunciated.

These different metrics for voice communication activity derive in part from researcher viewpoint, and in part from research objective. The work in [2], for example, is intended to find whether communication activity has an independent effect on controller workload after controlling for traffic activity, while work in [1], likewise, explores relationships between communication activity and controller workload. Other studies, such as [4] and [5], are concerned with how changes in the Air Traffic Control

(ATC) system (the introduction of free flight in the first case and of data link in the second) would affect communications activity.

Although the literature includes a wide variety of voice communication metrics, one aspect of the voice communication process has received scant attention. Individual voice messages are generally parts of multi-message transactions. For example, if a controller issues an instruction he/she begins a transaction that ends when the pilot sends an accurate readback. The duration of the transaction includes both the actual speaking time and the "dead" time between voice activity. In cases where there are readback errors, or delays resulting in the controller repeating an instruction, a single transaction may include multiple segments of voice time and "dead" time. Moreover, there may be periods when multiple transactions are open, as when the controller sends a message to a second aircraft prior to having heard back from the first.

The time periods during which transactions are open, even when they include no radio communication, are arguably different with respect to controller workload and stress than the time periods when there are no open transactions. The controller must retain the open transaction in working memory while performing other tasks. Also, the controller may feel inhibited from initiating other communications pending completion of the open transaction. Finally, a controller awaiting response to his/her voice message may feel a lack of personal control over his/her work situation, because completion of the transaction is up to the pilot. Such lack of control has been found to be a major cause of physical and psychological stress [6].

The distinction between transaction time and communication time is particularly important in the context of assessing data link as an alternative to voice communication. Data link lengthens transaction times as the result of delays in message transfer ("end-to-end transfer delay"—see [7]) and the time required for pilots to read and reply to controller messages. It has been estimated that en route transaction times for data link—defined as the time from the initiation of a message by the controller to the receipt of a pilot response—average around 20 seconds for data link as opposed to 10 seconds for voice [8], [9].

Current Practice

Today's primary means of pilot-controller communication still rely on traditional radios. Although the radio frequency bands are divided into high (HF), very high (VHF), and ultra high (UHF) spectrums, most of the routine air-to-ground communications use VHF and UHF spectrums only [10]. Military aircraft use UHF, while VHF spectrum is used by both civilian and military aircraft.

Due to the lack of available frequencies, the same frequencies are sometimes assigned to several sectors. Basically, pilots communicate with an air traffic controller by adjusting their aircraft VHF radio to a designated sector/controller frequency. Each controller is allocated (i) at least one radio frequency to communicate with pilots, and (ii) telephone to communicate with other controllers, either in the same center or other centers.

Problems with VHF Radio Communications

Radio frequency congestion quite often occurs in busy sectors when many aircraft attempt to communicate with an air traffic controller. Because each communication message takes a certain amount of time, it happens that during busy traffic periods there is a point of saturation on a communication channel where an air traffic controller cannot receive/transmit any additional messages. Consequently, during that period, no additional aircraft can be managed within the controller's assigned airspace. Errors, miscommunications and message repeats also contribute to the frequency congestion and unnecessary increase in the controller workload.

Other common problems with VHF radio communications are reflected in (i) poor quality, (ii) high susceptibility to interference and (iii) a high risk of blocked or "stepped on" transmissions [11].

Future Concepts

To overcome some of the deficiencies of the existing voice-communication system, a new concept for the exchange of controller-pilot communication messages was developed – Controller-Pilot Data Link Communication (CPDLC) system.

In a CPDLC environment, many messages would be transmitted via data link, which would consequently reduce frequency congestion and utilization. Controllers and pilots would use CPDLC displays and keys [12] to compose, send and receive messages (figure 1). CPDLC would facilitate many routine communication tasks. For example, altitude or route clearances would have a specific letter affixed to the computer input when a controller composes a message to be sent to the pilot. This letter would indicate that the computer must compose an altitude or route clearance message for transmission to the aircraft. When such a message arrives via data link to the cockpit, it would be shown to the pilot on the display. Then, a pilot would acknowledge that he received a message by pressing a specific key.

Figure 1. CPDLC Display for Pilots
(source: EUROCONTROL)

Problem Description

Although various metrics have been already defined for the analysis of controller-pilot communication activity and controllers' and pilots' workload, we postulate an additional metric that takes into account groups of messages consecutively used to finish one complete message "transaction" (this includes, for example, all messages used to complete an initial call or altitude change for one aircraft). Then, relations between physical (classical) utilization for radio channel frequency and traffic demand are explored and linked to the new metric. In this way, we can (i) investigate the impact that keeping track of open "transactions" has on controllers (in terms of "transaction" workload), and (ii) compare that impact to the workload that stems from voice communication per se (physical utilization is often used as a communication workload metric).

Methodology

We recovered and analyzed radio communications data obtained from a sample of controller-pilot voice recordings. Voice recordings were obtained from the FAA Technical Center and MITRE Corporation. Recordings were transcribed and the communication messages they contained categorized by message type, complexity, origin (controller or pilot), and aircraft ID.

Transcribed messages were time-stamped in order to enable calculation of duration of each message as well as the time between messages. Duration of each time interval was used to calculate the two metrics defined and explored in this study: cognitive utilization and physical utilization. The key steps of our methodology are depicted in figure 2.

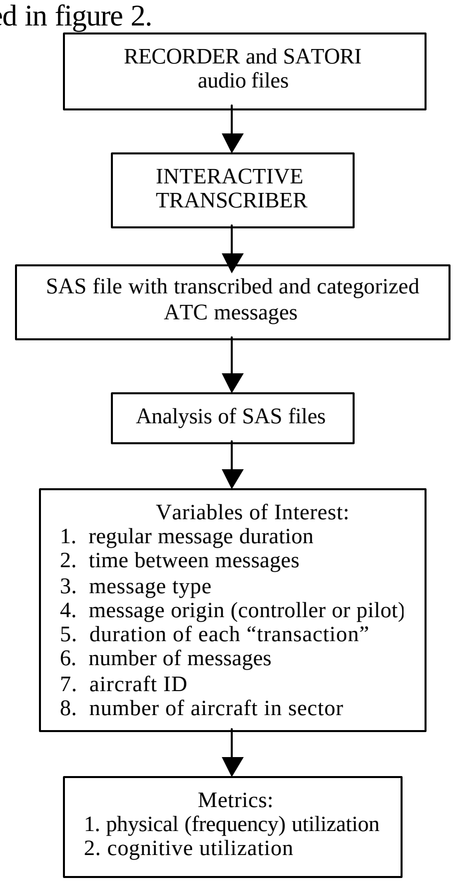

Figure 2. Methodology

3.1 Sample and Study Area

Our analysis is based on fifteen 30-minute controller-pilot voice recording samples, selected for various sector flight levels (FL), days (dates) and start times. These recording samples were derived from 7 sectors that are situated in 3 Air Route Traffic Control Centers (ARTCC). As indicated in table 1, sectors from Indianapolis ARTCC (ZID) include super high sectors (FL 330 and above), while sectors from Denver ARTCC (ZDV) and Atlanta ARTCC (ZTL) include high altitude sectors (FL 240 310). The selected sectors are of different physical sizes, and traffic demands to reflect sector-size variations and traffic demand fluctuations found in real-world situations.

Table 1. List of Selected Controller-pilot Voice Recording Samples

ARTCC	Sector Name (number)	Altitude Super High (FL 330 and above) High (FL 240 – 310)	Time Interval (ZULU)	Date
ZID	92	Super High	19:15 – 19:45	31/8/00
ZID	92	Super High	21:45 – 22:15	31/8/00
ZID	96	Super High	20:30 – 21:00	31/8/00
ZDV	14	High	14:47 – 15:17	9/7/00
ZDV	25	High	17:00 – 17:30	9/6/00
ZDV	25	High	16:47 – 17:17	1/23/01
ZDV	30	High	15:11 – 15:41	9/7/00
ZDV	30	High	21:55 – 22:25	9/7/00
ZDV	38	High	21:27 – 21:57	9/7/01
ZDV	38	High	16:19 – 16:49	9/6/00
ZDV	3	High	18:05 – 18:35	2/23/01
ZDV	3	High	15:36 – 16:06	9/6/00
ZTL	3	High	19:45 – 20:15	7/25/01
ZTL	3	High	20:30 – 21:00	8/11/01
ZTL	3	High	19:40 – 20:10	8/15/01

Definitions for Physical and Cognitive Utilization

We define our physical utilization metric (figure 3) as the percentage of time in the 5-minute interval during which frequency is occupied by either a pilot or a controller. Physical utilization is calculated by summing the time intervals in which either controller or pilots were communicating, and then dividing the sum by the total time interval (5 minutes).

Physical utilization P is thus defined as:

$$P = \frac{100\sum_{i=1}^{n} t_i}{T}, \text{ where}$$

t_i = duration of i^{th} message (sec),

n = total number of messages in T,

T = total time interval (sec).

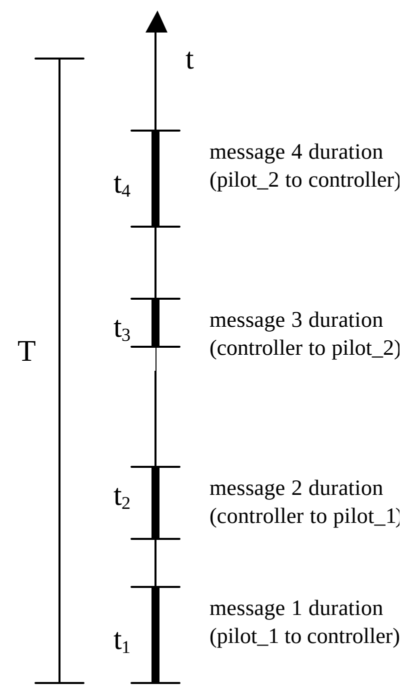

Figure 3. Physical Utilization for Radio Channel

Cognitive utilization (figure 4) is the main metric used in our study. The term “cognitive” is based on the idea that during the time when a given communications transaction is open the controller must continue to be aware of it. Our cognitive utilization metric is the sum of all the time intervals during which at least one communication “transaction” remains open. A “transaction” considers the time needed to complete (for example) the initial call, which would include time from the pilot’s initial call until the end of the controller’s acknowledgement of the pilot's call. Table 2 shows one of the communication "transactions" that was used to calculate cognitive utilization. All presented time intervals were summed up as cognitive utilization, according to the hypothesis that the controller has to pay attention to the specific aircraft at least as long as the specific communication lasts. This concept is also depicted in figure 4, which illustrates the difference between "transactions" and individual communication messages.

Cognitive utilization Q is thus defined as:

$$Q = \frac{100\int_0^T q(t)dt}{T}, \text{ where}$$

$q(t)$ = 1 if there is an open transaction at time t and 0 otherwise;

T = total time interval (sec).

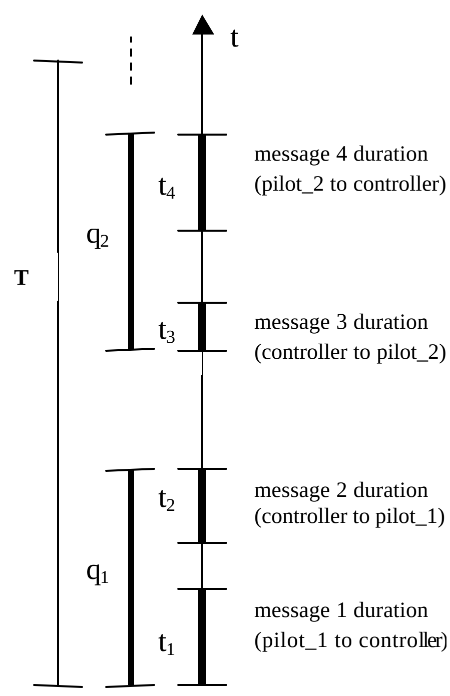

Figure 4. Controller's Cognitive Utilization

One or more transactions may be open when the cognitive utilization variable $q(t)$ is turned on. In the more common and simpler case, there is just one open transaction. There are cases, however, when a second transaction (or, conceivably, a third) is initiated while an earlier one is still open. This usually occurs when pilots do not respond promptly to an earlier controller message. An alternative cognitive utilization metric would "double count" time when two transactions are open.

Table 2. Cognitive Utilization Example – One Transaction

Message Issued by	Aircraft ID	Message Content	Message Duration (sec)	Time Between Messages (sec)
Pilot	XXX10	Indi XXXAirlines 10, checking in 3 3 0 smooth.	2.275	
				0.899
Controller	XXX10	XXXAirlines 10, Indi Center roger, did you have a request.	1.826	
				3.269
Pilot	XXX10	XXXAirlines, no.	1.372	
				0.359
Controller	XXX10	OK, thanks.	0.479	

We analyzed relationships between the metrics Q and P and a third measure, Count-to-Capacity Ratio (CCR). The CCR is the ratio of the number of aircraft present in the sector to the declared Monitor Alert Parameter (MAP) for the sector. MAP is defined as the maximum number of aircraft that should be allowed in the sector at a given time. We determined the number of aircraft in the sector by counting cumulative numbers of initial calls and handoff messages, correcting for the number of aircraft already present in the sector at the beginning of the recording (indicated by a handoff but no initial call on the recording).

Cognitive Utilization, Physical Utilization, and Sector Capacity

This section analyzes our voice and traffic data in order to determine whether cognitive utilization affects sector capacity. First, we investigate the relation between physical utilization and sector capacity. We then investigate whether there is an independent cognitive effect.

Figures 5 and 6 show the relations between count-to-capacity metric and physical utilization, and cognitive utilization, respectively. Table 3 shows the correlation coefficients for the mentioned relations. We can see that physical utilization has a stronger correlation with the count-to-capacity metric compared to cognitive utilization. This is to be expected because aircraft counts are more directly tied to the quantity of voice communication than to the quantity of transaction time.

Figure 7 compares the cognitive and physical utilization metrics across the data used. We can see that for the most part there is a close linear relationship between cognitive utilization and physical utilization. There are several cases, however, that follow a different pattern. Indeed, there is evidence of a "bifurcation" when physical utilization is in the 20-30% range. In the predominant branch, the linear relationship continues through P values of 60% or more. But in the alternative branch, P rarely exceeds 30% while Q extends to values from 50 to 100 percent. This is apparently a regime in which excessive cognitive utilization could limit physical utilization. Such a situation arises in four of the fifteen 30-minute observation periods.

Figures 8 through 11 show in more detail the cognitive and physical utilization metrics for the deviant observations. The utilization metrics are plotted for each 5-minute bin in the 30-minute observation period. From figure 8 we can see that while cognitive utilization generally tracks physical utilization, in the 10-15 minute bin, the cognitive utilization is much higher than the physical. Review of the transcript reveals that this was a case of delayed pilot response. Moreover, while waiting for response, the controller had to issue clearances to two other aircraft, resulting in multiple open transactions.

Figure 9 shows even bigger deviation between cognitive and physical utilization. In all the three cases of excessive cognitive utilization, miscommunications and delayed responses were present. In the first case (the 5-10 minute bin), a pilot "stepped on" the transaction that was already in progress. The second and the third case involved a pilot that was not responding to the controller's calls. In all three of these cases the cognitive utilization accounted for multiple open transactions.

Figures 10 and 11 show cases where for the most part the cognitive utilization follows physical utilization, pointing to the fact that the communications did not involve miscommunications of any kind. In both figures there is at least one instance where the cognitive utilization is much higher than physical. Transcript review reveals that in the case depicted in figure 10, there was a problem of delayed pilot response. The controller called the pilot with a handoff message, to which the pilot did not respond. In contrast, two points that "jump out" in the figure 11 are caused by a different situation. The first point is at the time interval 15, which featured several lengthy communications conveying weather-related clearances and information. Also, there was a miscommunication in which the controller did not understand the initial call and needed two repetitions to make sure of the aircraft with which he was communicating. In the second point, there was a request for the weather related information, for which the controller needed to call another aircraft. As the result of bad radio connection (static), the weather information transaction was prolonged and needed repeating.

Informal conversations with controllers reveal that delayed pilot response is one of the major sources of workload and annoyance. The cognitive utilization metric is one way of quantifying these effects. However, because of the data constraints we were not able to investigate directly the relation between cognitive utilization and workload. This is an area for future research.

Table 3. Correlation between Chosen Metrics and Count-to-Capacity

Metric	Correlation
Cognitive Utilization and Count-to-Capacity	0.545
Physical Utilization and Count-to-Capacity	0.727

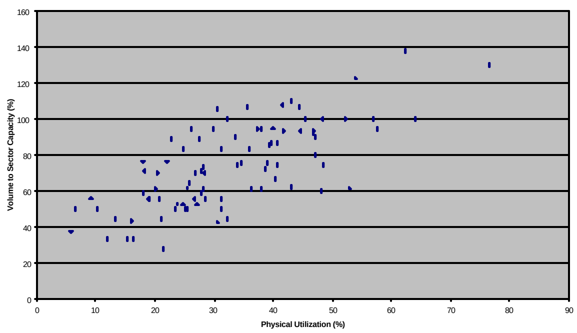

Figure 5. Physical Utilization vs. Count-to-Capacity Ratio for 15 Sectors

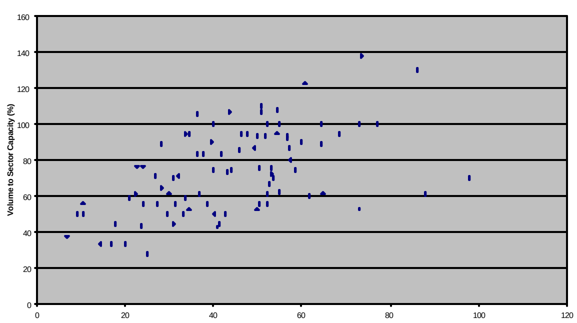

Figure 6. Cognitive Utilization vs. Count-to-Capacity Ratio for 15 Sectors

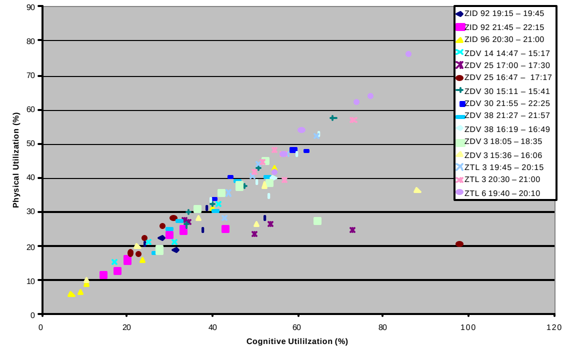

Figure 7. Cognitive vs. Physical Utilization for all Sectors

Table 4. Sector Characteristics: Utilizations, Ratio, and Correlation

Sector Name (number)	Time Interval (ZULU)	Average Cognitive Utilizat. (%)	Average Physical Utilizat. (%)	Ratio Physical to Cognitive	Correl. Coeff.
ZID 92	19:15 – 19:45	35.30	24.40	0.69	0.714
ZID 92	21:45 – 22:15	26.22	19.15	0.73	0.945
ZID 96	20:30 – 21:00	24.17	18.60	0.76	0.997
ZDV 14	14:47 – 15:17	28.61	22.43	0.78	0.956
ZDV 25	17:00 – 17:30	46.73	26.74	0.57	-0.629
ZDV 25	16:47 – 17:17	37.44	22.08	0.58	-0.060
ZDV 30	15:11 – 15:41	45.78	37.68	0.82	0.991
ZDV 30	21:55 – 22:25	51.00	42.74	0.83	0.960
ZDV 38	21:27 – 21:57	53.63	41.17	0.76	0.882
ZDV 38	16:19 – 16:49	37.89	30.21	0.79	0.957
ZDV 3	18:05 – 18:35	45.90	33.63	0.73	0.452
ZDV 3	15:36 – 16:06	51.42	41.32	0.80	0.939
ZTL 3	19:45 – 20:15	43.42	26.53	0.61	0.853
ZTL 3	20:30 – 21:00	57.14	46.30	0.81	0.820
ZTL 3	19:40 – 20:10	68.10	57.49	0.84	0.983

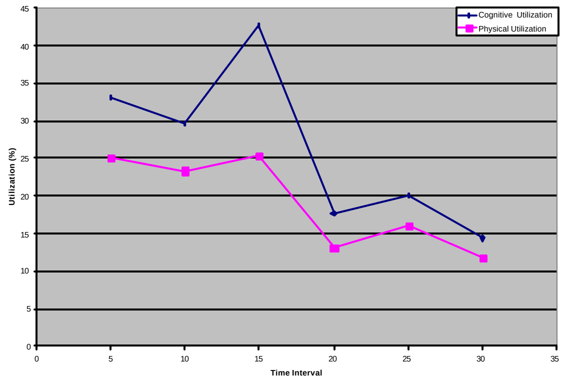

Figure 8. Cognitive and Physical Utilization for ZID 92, time 21:45-22:15

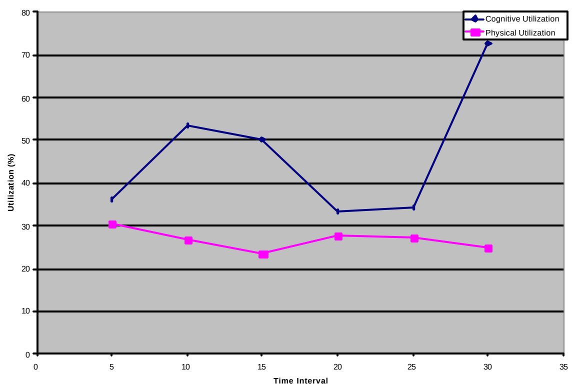

Figure 9. Cognitive and Physical Utilization for ZDV 25, time 17:00-17:30

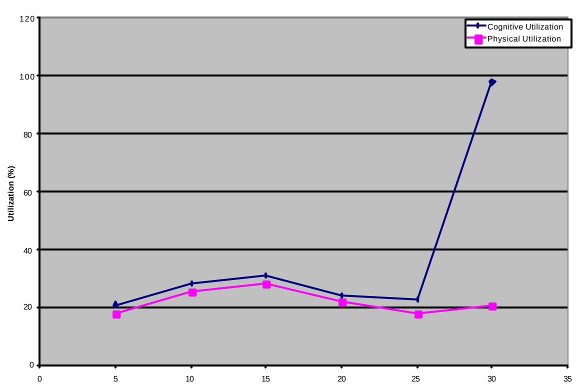

Figure 10. Cognitive and Physical Utilization for ZDV 25, time 16:47-17:17

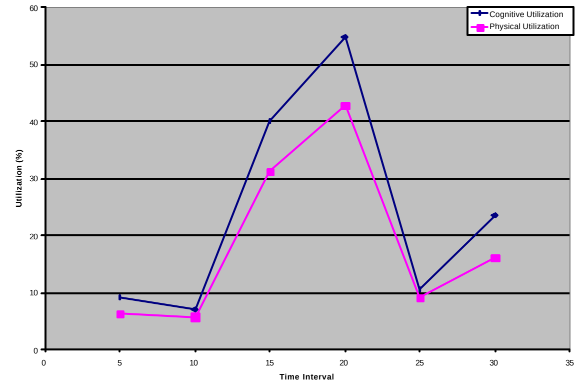

Figure 11. Cognitive and Physical Utilization for ZID 96, time 20:30-21:00

Conclusions and Recommendations

For the purpose of understanding effects which impede controller-pilot communications, we have proposed a new metric which allows analysis of the duration of transactions rather than the volume of voice traffic. The new metric is motivated by the supposition that controllers' cognitive resources are absorbed by open transactions as well as by communication activity per se. Because CPDLC, while reducing voice communication time, is expected to increase transaction time, it is important that this effect be understood.

The introduction of CPDLC into the ATC environment is causing a change in the controllers' tasks and in the workload distribution. Traditional metrics, such as time spent communicating, number of communication events, or number of communication events by category – to mention just a few, are no longer the appropriate indicators of communication workload. Cognitive utilization is a metric that can be easily applied in the new environment, since it takes into account all the open transactions (it can account for voice, as well as data link transactions). As such, cognitive utilization is a better metric for addressing the influence of increased transaction time (CPDLC environment) on the controller workload and/or controller situation awareness. Further research is needed to establish the nature of relationship between the cognitive utilization metric and the controller communication workload and situation awareness.

Our results suggest that, most of the time, cognitive utilization and physical utilization are highly correlated. In these cases, there is little value in having two different metrics. However, in 25% of the 30-minute observation periods studied, there is at least one case in which cognitive utilization vastly exceeded physical utilization. Sometimes this is the result of delays in pilot response to controller messages; in others there is actual miscommunication. Whatever the cause, we find that in these cases physical utilization remained well below the maximum levels observed across all cases. This supports the hypothesis that high cognitive utilization can significantly diminish communication capacity. This also shows that the cognitive utilization encompasses additional information about "out-of-the-ordinary" communication events, mostly some sort of miscommunication. As already mentioned, miscommunications are cited as one of the major sources of controller stress. Therefore, the future research should address the cognitive utilization relations to the controller communication workload and the controller situation awareness.

Another area of research on the cognitive utilization metric lies in refining the metric itself. As already mentioned, cognitive utilization sometimes tracks several transactions that are open concurrently. This needs to be given further thought because the strain on the controller cognitive resources rises with the number of open transactions. The nature of this relationship needs to be ascertained (whether it is linear or non-linear.

These conclusions are obviously tentative given the limited sample of voice communications that we have studied. Further work is necessary to validate our empirical findings and refine our explanations for them. Our future research should focus on the inter-relationships between cognitive utilization, workload, situation awareness, and controller performance. The impending shift from voice to data link communications makes research in this area an urgent need.

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