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Initial Implications of Automation on Dynamic Airspace Configuration

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The dynamic airspace configuration concept strives to remove today's rigid structure of navigation aids, airways, pre-defined sectors of airspace, and special-use airspace to provide traffic managers with more flexibility to reconfigure airspace to address convective weather and meet fluctuations in user demand. The impact of increasing levels of air traffic management automation on controller workload and airspace capacity is analyzed. The automation levels represent a current operations baseline; seamless, integrated datalink operations; and automated airspace operations in which separation, merging and spacing guidance is provided for 33,000 ft and above without human controller involvement. Denver Center traffic and airspace for a good weather day are modeled to predict the effect of increased controller productivity on airspace configuration strategies. Results indicate that integrated datalink operations enable the high and low altitude feeder sectors for Denver arrivals to be combined into a single sector for the selected traffic demand, facilitating more uninterrupted descents than possible under current operations. Furthermore, results indicate automated airspace operations enable a single en route sector team to manage airspace below 33,000 ft that is a combination of 5 of today's sectors.

I. Introduction

THE goals for the Next Generation Air Transportation System (i.e., NextGen) are aimed at significantly increasing the capacity, safety, efficiency, and security of air transportation operations. The Joint Planning and Development Office (JPDO) expects that NextGen will need to accommodate up to three times today's traffic levels by 2025.[1] To meet these demands, JPDO envisions significant transformations in air traffic management (ATM) in the following areas:

- Trajectory-Based Operations
- Performance-Based Operations and Services
- Collaborative Traffic Flow Management
- Allocation of Airspace
- Separation Management
- Weather/Automation Integration

These six interdependent areas will provide the Air Navigation Service Provider (ANSP) with the necessary capacity and flexibility to meet the needs of the NextGen users. The National Aeronautics and Space Administration (NASA) is working with JPDO to further develop these areas of research. In particular, NASA is developing the "Allocation of Airspace" concept area, referred to in this paper as Dynamic Airspace Configuration (DAC).

A primary goal of ATM is to balance capacity and demand. In today's Air Route Traffic Control Center (i.e., Center) operations within the National Airspace System (NAS), airspace capacity can be constrained by weather, special use airspace (SUA), and controller workload. Convective weather and SUA can constrain capacity by

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occupying volumes of airspace and making them temporarily unusable. In contrast, high levels of projected controller workload can constrain capacity by requiring that traffic flow management (TFM) restrictions be imposed upon the traffic upstream of the projected sector congestion to prevent controller overload. For this paper, this imbalance between traffic demand at the sector level and acceptable levels of controller workload is referred to as *workload-constrained capacity*. In today's operations, workload-constrained capacity is specified by the Monitor Alert Parameter (MAP) which is a recommended upper bound on the acceptable number of aircraft in a sector. (Although not addressed in this paper, the MAP will most likely be replaced in future operations with a parameter that more closely represents traffic complexity, which research has shown to be a better predictor of controller workload than simple aircraft count.[2])

A. Problem Description

In today's Centers, a rigid structure of navigation aids, airways, sectors of airspace, and SUA has evolved to attempt to meet user demands. However, airspace capacity is limited because of the traffic managers' restricted flexibility to reconfigure sectors to address convective weather and/or meet fluctuations in demand. The combining and splitting of sectors within a pre-defined volume of airspace and the opening and closing of SUA are the only tactical techniques currently available to reconfigure airspace. Because of these limitations, demand management is increasingly necessary to resolve the growing capacity/demand imbalance. Ideally, demand management should only be utilized as a last resort – after airspace capacity management strategies are exhausted – rather than as a first line of defense. At today's traffic levels workload-constrained capacity is a relatively small bottleneck as compared to weather or airport capacity constraints. However, the "3x" traffic level forecast for 2025 mentioned earlier, in addition to air carrier strategies that may exploit under-utilized airports, will significantly amplify this workload-constrained en route capacity problem if the current airspace design paradigm and automation levels were to remain essentially unchanged over the next two decades. Furthermore, a reliable means for predicting workload-constrained capacity of NextGen concepts is needed.

B. Proposed Solution

In NextGen, demand management is allocated to the Collaborative Traffic Flow Management whereas capacity management is primarily allocated to DAC. A major component of DAC is to optimize the airspace design across the NAS to maximize capacity of workload-constrained airspace while addressing weather and SUA. It is expected that airspace design optimization will be applied across time horizons of varying scale – from year to month to day to hours. For example, annual airspace configuration would include major infrastructure changes such as new runways. Monthly changes would account for seasonal demand and weather patterns. Daily changes would consider preplanned demand, forecasted conditions (e.g., jet stream), and SUA. Hourly changes would reflect convective weather, closed airports due to extreme weather, and SUA. By configuring airspace in this manner, it is anticipated that this large-to-small scale of time horizon will result in more stable airspace configurations than would otherwise be possible.

The Performance-Based Operations requirements of NextGen are expected to enable the creation of new classes of airspace such as autonomous self-separating airspace, in which pilots of properly equipped aircraft are permitted to enter and assume responsibility for separation. Since the task for maintaining safe separation has been offloaded from the controller, this should allow controller productivity[§] to be increased and enable the controller to handle more aircraft. It is expected that separate traffic complexity metrics will be developed for each new airspace class, since traffic complexity will mean something different for each class and will have different impacts on controller productivity as well. Furthermore, while ATM automation and airspace configuration are expected to provide airspace capacity increases independent of the other, the synergy between the two should provide capacity greater than the sum of the parts. Lastly, the NextGen infrastructure will support flexible staffing of the NAS. Airspace-specific domain knowledge and airspace configuration will be standardized so that controllers can work a robust range of airspace within the airspace class that they are certified to manage.[3]

Analysis of a concept known as the Airspace Playbook is also being performed.[4] This concept is an extension to the National Severe Weather Playbook in which a predetermined, optimized airspace design is coupled to each weather avoidance play (a predetermined set of routes) so that the resulting airspace configuration maximizes workload-constrained capacity. Research closely related to DAC is being conducted by Eurocontrol for a concept

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[§] New controller and ATM tools and technologies such as datalink and automatic dependent surveillance – broadcast (ADS-B) have the potential to reduce controller workload on a per aircraft basis. However, the overall goal is not to reduce controller workload, but rather to maintain workload at today's levels while making controllers more productive through use of these tools and technologies so they can manage more aircraft in a sector. This idea is referred to as increased controller productivity.

referred to as the Freeway System for Europe.[5] This concept, proposed for the congested skies of Western Europe, requires aircraft to follow a grid of freeways in the sky where altitude is determined by the desired direction of flight.

The motivation and significance of this research is to present initial implications of configuring airspace based on increased controller productivity resulting from increasing levels of ATM/aircraft automation. For traffic demand not exceeding today's MAP values, increased controller productivity enables larger volumes of airspace to be managed by a single controller team. Alternatively, for traffic demand exceeding today's MAP values, increased controller productivity permits larger traffic levels for a given airspace configuration (see Figure 1) without the need for *workload-constrained* TFM restrictions (however, TFM restrictions to account for weather or airport capacity limitations would still be required). Although a blending of these two approaches provides the optimal airspace configuration, the initial analysis presented in this paper focuses on the former (traffic demand within today's MAP values) since as-flown operational data was utilized; thus, any excess in demand would have been mitigated by TFM. It is worth noting that a human-in-the-loop study with similar goals has been conducted.[6]

II. Background

The Center Controller Performance Model (CCPM) is a continuously evolving human performance modeling tool in which controllers and pilots are represented as computational entities. These entities are modeled to interact with ATM system elements just as real controllers and pilots would in today's operations or simulated future operations. In 2002, the fidelity of CCPM was increased for the cost benefit assessment of air and ground concepts to predict the impact of increased controller productivity on workload-constrained capacity.[7] In 2005-2007, extensive research was conducted to validate CCPM against FAA Future En route Work Station (FEWS) controller-in-the-loop simulation data collected for traffic levels that varied from 100% of today's traffic to 166%.[8] In particular, this validation effort added significant realism to way the simulated controllers detect airspace events (e.g., conflicts, metering conformance problems, and sector transitions).

CCPM has thus far evolved into a highly complex model representing current and future controller roles and responsibilities; workload prediction modeling; visual attention; task prioritization; sophisticated heuristics for conflict resolution, spacing, and merging; and interactions with controller-pilot datalink communication (CPDLC), Traffic Management Advisor (TMA), and En route Descent Advisor (EDA). CCPM enables concepts to be evaluated, in part, based on whether the concepts demonstrate increases in both controller productivity and Center capacity. (Note that terminal airspace is not typically constrained by workload limitations, but rather due to airport capacity constraints. Staffing levels in terminal airspace are apportioned to ensure that full airport capacity is achievable.) A controller's display system has been closely replicated to depict controller actions and activities via the computer readout display (CRD) and to address display clutter issues. Furthermore, the simulated controller display also graphically represents instantaneous workload and voice and datalink communications. CCPM utilizes the commercially-available Micro Saint Sharp discrete event simulation tool environment[9] for model definition and execution. Programming is written in the C# language.

III. Technical Approach

The approach of this study was to first select a Center and an area of specialization within that Center that is not routinely subjected to TFM restrictions. Next, traffic demand was selected based on nominally busy, good weather days in the summer of 2006. After that, airspace configurations strategies associated with three different levels of ATM automation were developed. Lastly, using CCPM, all of the above was simulated to predict controller workload and determine if the airspace configurations were feasible from a workload perspective. Further details are provided below.

A. Airspace Description

As this research is an initial study to assess reconfiguration strategies, the intention was to select airspace that 1) is not routinely subject to TFM restrictions (other than TMA spacing, which is easily managed in CCPM because of a well-defined freeze horizon) because of the complexity in converting as-flown trajectories to their "pre-TFM restricted" conditions; 2) provides good potential for future DAC studies. Area 1 of Denver Center (ZDV), which includes the northwest cornerpost of the Denver Terminal Radar Approach Control (TRACON), was selected. Area 1 exhibits the types of traits that DAC would most likely address. For example, significant convective weather will occupy Area 1 several times during the summer, particularly near the arrival gate. Since Denver International Airport (DEN) is a major hub for United and Frontier Airlines, disruptions due to convective weather can affect operations across the NAS. In addition, during the holiday ski season, the number of light aircraft destined for Aspen and Eagle (near Vail) and other ski destinations can significantly exceed the low altitude sector's MAP. Neither of these issues is addressed in the current study; however, the results will serve as a useful baseline for future DAC investigations of convective weather impacts and low altitude sector congestion.

Much of the air traffic passing between the east and west coast passes through ZDV airspace. Area 1 covers the airspace immediately west of DEN. The airspace serves DEN by providing arrivals through the RAMMS and TOMSN arrival gates and west departures through the ROCKIES departure. Arrival aircraft coming through RAMMS and TOMSN are generally from the west coast. Area 1 is made up of eight sectors. Four of the sectors are high altitude (see Figure 1), containing airspace at and above FL270. Most of the traffic flow is east/west through the sectors. Sector 03 is responsible for much of the DEN departure traffic that is heading west and northwest. Sector 04 is responsible for much of the DEN departure traffic that is heading west and southwest, especially Los Angeles area traffic. Sector 05 is responsible for transitioning departure aircraft from the Denver TRACON into the en route environment. Sector 14 is responsible for metering and descending the DEN arrival traffic coming through the RAMMS and TOMSN gates. The low altitude sectors (see Figure 2) contain airspace from the surface up to FL269. Table 1 lists the MAP values for the sectors in Area 1.

Table 1. MAP values for sectors in ZDV Area 1.

Sector	MAP value
03	21
04	21
05	19
11	11
12	15
06+13	14
14	21

Note that sectors 06 and 13 are almost always combined during nominal operations so the modeling studies also assume they are combined. For brevity, this combined sector will be referred to simply as sector 13 hereafter. In general, the MAP value is a function of average sector flight time – the smaller the flight time, the smaller the MAP value.[10] Furthermore, low altitude sectors have smaller MAP values than high altitude sectors, because low altitude sectors have responsibility for takeoffs from and landings to non-towered airports in their airspace.

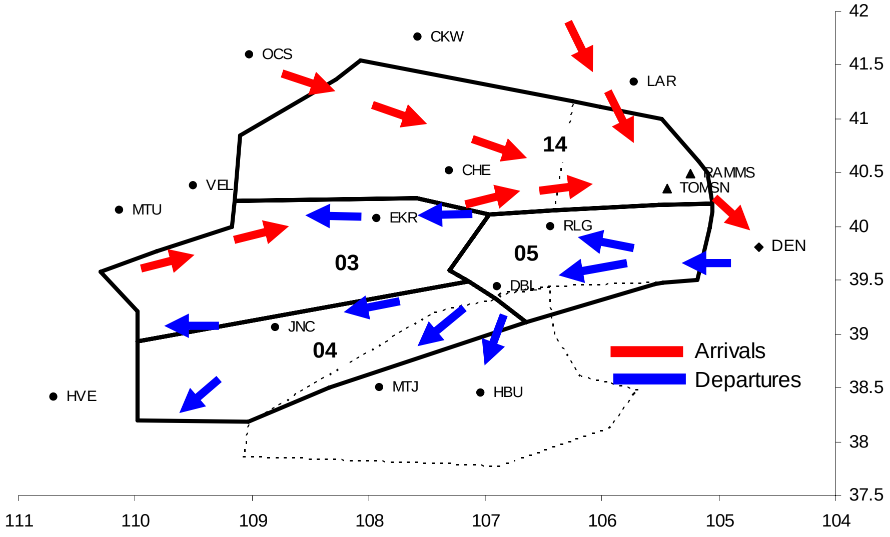

Figure 1. High altitude sectors in Area 1 of Denver Center. *Low altitude sectors are outlined with dashes. Major fixes are also identified. Lon/lat specified on x- and y-axis, respectively.*

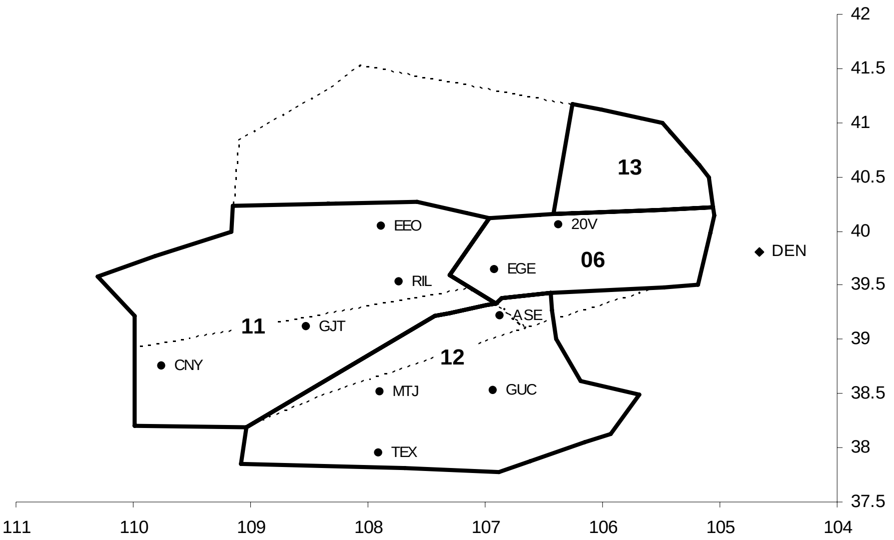

Figure 2. Low altitude sectors in Area 1 of Denver Center. *Locations of smaller airports shown. High altitude sectors are outlined with dashes. Lon/lat specified on x- and y-axis, respectively.*

B. Traffic Description

The goal of incorporating ETMS traffic into CCPM for Area 1 of Denver Center was to find nominally busy days in the summer of 2006 that were neither subject to significant convective weather in Denver Center nor convective weather elsewhere in the NAS to avoid any National Playbook rerouting. Two Fridays in June that met this criteria were selected – June 16 & 30. Analysis of the "as flown" data determined that the most consistently busy hours of traffic for Area 1 was June 16, from 8:45 am to 11:15 am local time. The "as flown" trajectories were manually converted into trajectories where conflict resolution and spacing maneuvers were removed – effectively restoring the aircraft to their pre-conflict resolution or pre-spacing state. This step was necessary so the simulated controllers in CCPM would have conflict resolution and spacing tasks to perform and the associated workload could then be calculated and recorded.

C. Automation levels

The automation levels represented in this study are:

1) A baseline condition representing Current Operations which includes a representation of User Request Evaluation Tool (URET) and TMA.
2) The addition of seamless, Integrated Datalink Operations. This means that the transfer of communication task by the transferring controller and the pilot call-in task to the receiving controller are eliminated because the system automatically sends the aircraft the new radio frequency upon handoff receipt. In addition, common communication tasks, such as crossing a meter fix at a specified speed and altitude, are available from a drop-down list and sent with a click of the trackball. Lastly, any messages sent via datalink to change altitude, heading, speed, or route automatically update the En Route Automation Modernization (ERAM) system with this intent information.
3) The last automation level, Automated Airspace Operations, corresponds roughly to the end-state of NextGen in which automation provides detection and resolution of conflicts. In addition, the automation provides trajectory changes required for conflict-free metering conformance. The study assumes the automation can provide a look-ahead time of 15 min for conflict detection and resolution, and 20 min for metering conformance. Only aircraft with the proper automation equipage are permitted to enter the automation airspace, which the study assumes corresponds to all airspace in ZDV Area 1 that is at FL330 or above. A normal handoff process is assumed for all flights departing/descending from the automation airspace to the staffed airspace below. If the handoff of a descending aircraft is not accepted by the staffed sector in a timely manner, the aircraft must level off at FL330. For departures, the automation clears climbing aircraft into the automated airspace. Lastly, the study assumes that the automation level for airspace below FL330 represents Integrated Datalink Operations as described in #2.

D. Airspace Configuration Strategies

As automation increases controller productivity, the controller will be able to manage more airspace. Integrated Datalink Operations primarily reduces the workload for tasks associated with sector transitions and communication, but does not explicitly affect tasks associated with separation or spacing. Thus, an assumption is made to keep arrival and departures segregated in terms of airspace configuration for Integrated Datalink Operations. On the other hand, there is a desire to facilitate trajectory-based operations. One way to do this is to combine the high and low sectors that feed the NW arrival gate of DEN (sectors 14 and 13, respectively). In this manner, a single sector team will be able to oversee an aircraft from cruise altitude to the TRACON boundary, providing uninterrupted descents and smooth merging prior to RAMMS or TOMSN. Similarly, another reasonable merging of sectors is to combine the remaining high altitude sectors 03, 04, 05 as these sectors primarily handle DEN departures as well as overflights.

For the Automated Airspace Operations, FL330 and above is automated for separation and metering so there is no controller workload associated with any tasks/functions performed at FL330 or above other than receiving the handoff of a descending aircraft as it transitions to staffed airspace. Between FL330 and FL270, high altitude sectors 03, 04, 05, 14 as well as the low altitude arrival sector 13 will be merged into a single airspace. Again, the combining of 13 and 14 facilitates uninterrupted descents through Center airspace.

E. Computational workload

CCPM uses a computational workload methodology which decomposes workload into visual, auditory, cognitive, and motor channels (VACM).[11] This theory assumes that the VACM channels are independent of each other for a given task. The scale for each channel ranges from 0 (no workload) to 7 (very high workload). The visual and auditory channels refer to the signal detection required for a task. The cognitive channel consists of the information processing and the motor channel is the physical action (e.g., speech, keystrokes) required to accomplish a task. Multi-tasking is modulated by ensuring that any two tasks performed concurrently do not exceed the threshold of 7 for any channel. Thus, numerical VACM scores above this threshold are not seen in CCPM because the scheduler accounts for the excessive task demand by postponing or shedding concurrent tasks accordingly.

Average workload is a useful parameter for characterizing relative differences between a baseline condition and a condition that represents a future concept. Average workload over a time period of interest (for this study, a running average over a 5 min duration is used) is expressed by:

$$WL_{i\ avg} = \sum_{j=1}^{n} \frac{WL_{i,j}\Delta t_{i,j}}{t_{total}}$$

where i is the VACM channel, j represents each task element executed by the model (e.g., move hand to track ball, read value from display), n is the number of task elements executed over the total time duration, $WL_{i,j}$ is the VACM workload of each task element, $\Delta t_{i,j}$ is the duration of the task element, and t_{total} is total time duration to average across. Note that the $WL_{i,j}$ values are VACM channel inputs assigned by the modeler for every possible task element to be performed whereas $\Delta t_{i,j}$ is calculated during run-time using micro-models of human performance such as Fitt's law or speech duration based on the number of words in the message.

IV. Results

A. Representative task comparison across automation levels

To give the reader an overview of the automation levels impact on controller workload, an example of the controller tasks and activities as a function of automation level is shown in Figure 3 for a representative DEN arrival aircraft. The controller tasks for SkyWest 6676 are listed beginning with the aircraft's entry into ZDV via sector 03 at a cruise altitude of FL330, traversing and descending through sectors 14 and 13, and then ending with its transition from sector 13 to the Denver TRACON at an altitude of 17000 ft. A reduction in controller activities from Current Operations to Integrated Datalink Operations is quite evident as Integrated Datalink Operations eliminate the transfer of communication and pilot call-in tasks. In addition, since sectors 13 and 14 are combined for Integrated Datalink Operations, the workload associated with the handoff between these sectors is eliminated and only a single descent clearance is required. Thus, the number of tasks corresponding to SkyWest 6676 is reduced from 15 for Current Operations to 6 for Integrated Datalink Operations.

The Automated Airspace Operations allows furthering reduction in controller tasks, requiring only 3 controller tasks since the spacing task associated with metering is now done in the automated airspace rather than staffed airspace. In addition, the amount of time that SkyWest 6676 resides in staffed airspace (airspace below FL330) is decreased from 36 min for both Current and Integrated Datalink Operations to 8 min for Automated Airspace Operations.

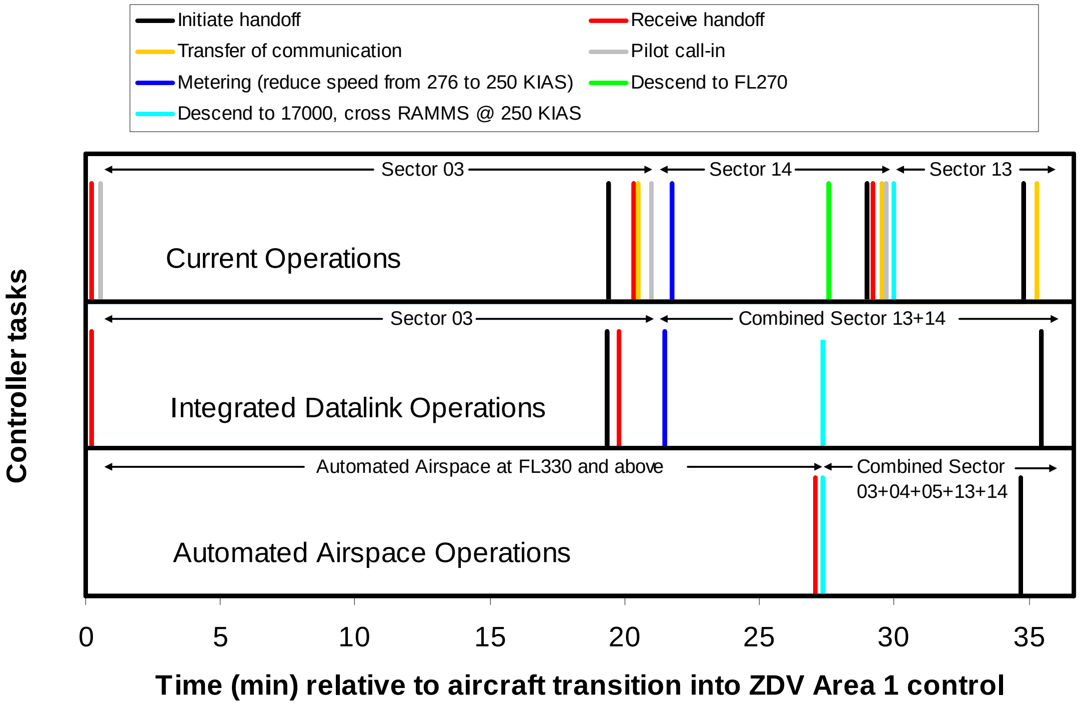

Figure 3. Controller task timeline comparison for representative DEN arrival aircraft.

B. Aggregate task comparison across automation levels

Figure 4 provides a comparison of the number of tasks performed by all Area 1 controllers across automation levels under two categories. The first category, sector transition tasks, occurs frequently, but is relatively simple in terms of the required cognitive processing. For Current Operations, these tasks are initiating and receiving handoffs, transfer of communication, and pilot call-in. The sector transition tasks for Integrated Datalink and Automated Airspace Operations are initiating and receiving handoffs only. Note that a considerable part of the reduction in sector transition tasks for both Integrated Datalink and Automated Airspace Operations is due to the combining of sectors, which eliminates a number of sector transitions that would otherwise occur for many of the aircraft flying across Area 1 airspace.

The second category, control tasks, which includes climb and descent clearances, conflict resolution, and metering, is more demanding for the controller compared to the first category because it requires more cognitive and visual processing to ensure separation and/or spacing is achieved. Comparing Current Operations to Integrated Datalink Operations shows a small reduction in control tasks (from 183 to 180). This reduction is due to the uninterrupted descent facilitated by combining sectors 13 and 14 for Integrated Datalink Operations. Under Current Operations, three DEN arrival aircraft were required to level off at FL270 (the floor of high altitude sector 14) because the low altitude sector 13 controller did not accept the handoff prior to the aircraft reaching FL270. These same three aircraft under Integrated Datalink Operations received a single descent clearance to 17000 ft. Lastly, the considerable reduction in control tasks for Automated Airspace Operations is largely due to metering conformance being performed in the automated airspace for DEN arrival aircraft at or above FL330.

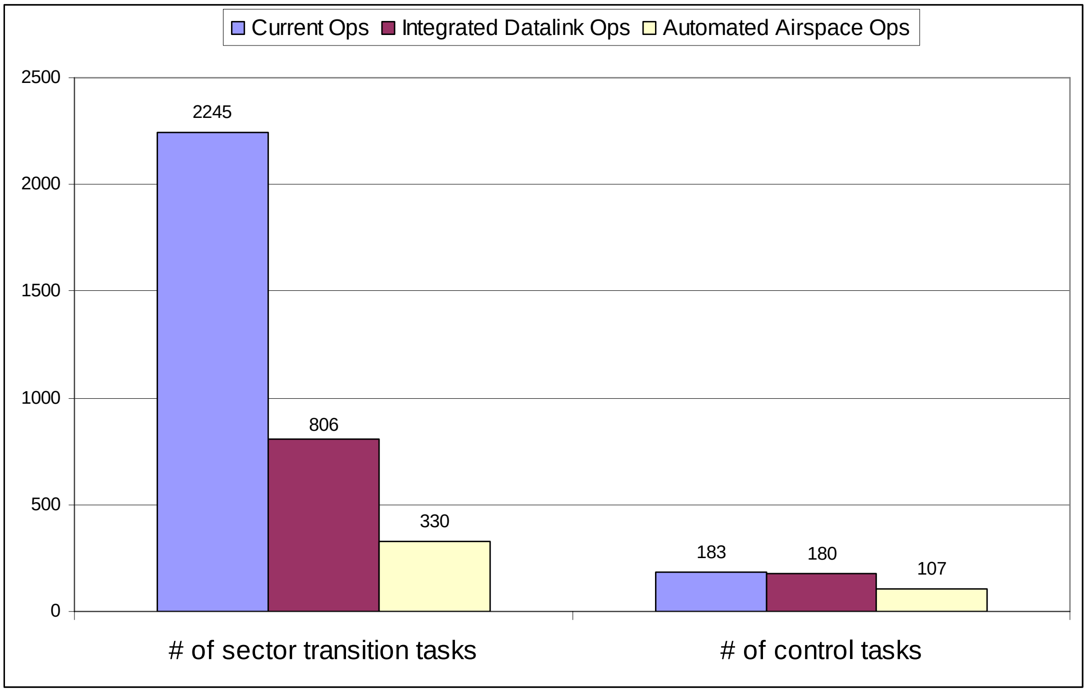

Figure 4. Comparison of the total number of tasks performed by Area 1 controllers for each type of automation level.

C. Predicted workload under Current Operations

Figure 5 shows the aircraft count, normalized by each sector's respective MAP value, for the baseline airspace configuration of ZDV's Area 1 for the period of interest. Based on normalized aircraft count, sectors 03 and 14 (plot 1 and 5 of Figure 5, respectively) are the busiest sectors during this period. Sector 03 experiences 85% of MAP at 50 min and 75% of MAP at 115 min. An arrival rush for sector 14 of 90% of MAP (19 aircraft) is evident at 130 min with 16-17 aircraft in the sector for a 15 min period. Traffic at or slightly above the MAP value for purposes of establishing a feasible workload benchmark would have been desirable. However, since this was not the case with the traffic sample selected, other methods were needed. With regards to the arrival rush, the MAP value = 21 for sector 14. For the sole purpose of establishing a computational "feasible workload" benchmark, a side-study was performed in which some arrival aircraft were cloned, staggering their start time to represent realistic spacing between aircraft, to increase sector 14's aircraft count to match its MAP value of 21. Assuming a 5 min running average, the peak workload value was calculated and all subsequent workload values are normalized by this amount as presented in Figure 5. For purposes of this study, this peak workload value represents the feasible workload limit and it is assumed that this value is applicable to all sectors in the analysis and for all three automation levels. Thus, when sectors are combined based on an automation level for subsequent analysis in sections D and E, the workload must remain near to or below this normalized value for the combining of sectors (and resulting traffic levels) to be considered feasible.

As shown in plot 5 of Figure 5, sector 14's peak normalized workload is 91% of the feasible workload benchmark, which is well within expectations since the peak aircraft count is 90% of the MAP. Normalized workload predictions for sectors 03, 04, 05, and 13 (plots 1 - 4 in Figure 5) remain well under the feasible workload benchmark, with no workload predictions higher than 0.77. Note that during periods of low traffic levels (aircraft count < 33% of MAP), the normalized workload predictions are consistently higher than normalized aircraft count (e.g., sector 05 in plot 3 of Figure 5). The primary reason for this divergence is CCPM assumes the simulated controllers monitor the display continuously under all traffic levels. In contrast, human controllers can take small, discrete breaks from monitoring under low traffic levels without impacting their ability to detect events in a timely manner. Thus far the study has not attempted to account for these realistic breaks in monitoring behavior in CCPM because the focus of CCPM studies has been high traffic, high workload scenarios where continuous monitoring is required.

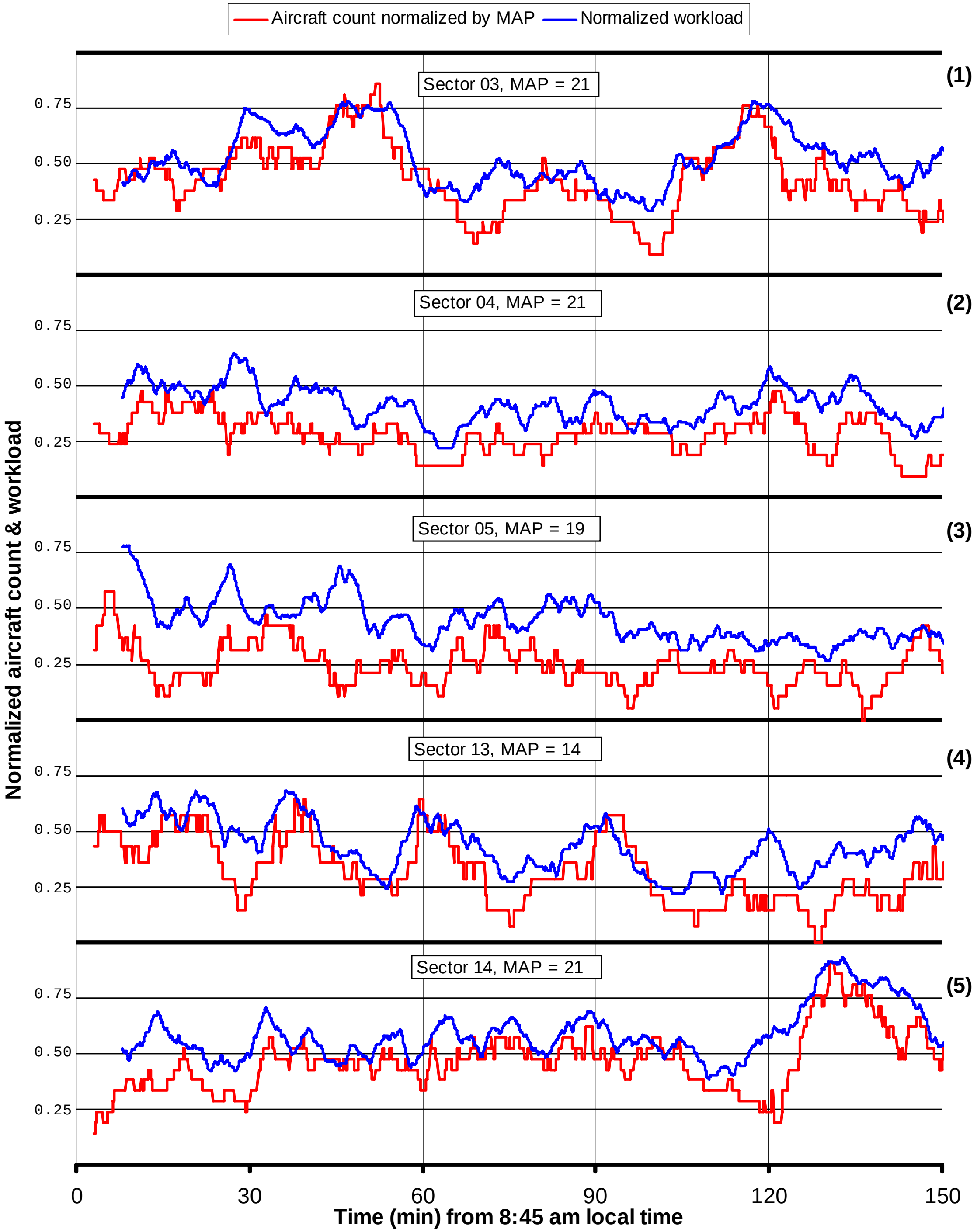

Figure 5. Aircraft count and predicted workload for Current Operations. *Each sector's aircraft count is normalized by its respective MAP value.*

D. Predicted workload under Integrated Datalink Operations

Plot 1 in Figure 6 shows the aircraft count and workload predictions for combining sectors 13 and 14 as facilitated by Integrated Datalink Operations. Note that aircraft count is not normalized by MAP value in Figure 6. This is because MAP values for Integrated Datalink Operations do not currently exist. The feasible workload limit is slightly exceeded at time around 20 min and again at 35 min. The maximum combined aircraft count for the combined sector 13 & 14 is 21 (at time = 134 min), coincidentally the same as sector 14's MAP value. Thus, it might seem reasonable that even under Current Operations, sectors 13 and 14 could be combined for this scenario. However, because sector 13 (with a MAP of 14) and its aircraft flight times through the sector are considerably smaller than sector 14 (due to its smaller horizontal footprint – see Figure 2), having 21 aircraft in the sector 13 portion of the combined airspace would cause sector transition workload problems for the controller. Analysis of task activity during the time period around 20 min and 35 min indicates that the controller of the combined sector is quite busy, initiating new tasks approximately every 15 – 20 s, with a majority of tasks related to aircraft in the sector 13 portion of the combined airspace. The significance of this result is that care must be taken when combining airspace volumes that create traffic flows with large variations in average sector flight time because of potential sector transition workload issues.

Plot 2 in Figure 6 shows the results for combining departure sectors 03, 04, and 05. Although there are more aircraft (peak count is 28) in this combined sector compared to the combined sector 13+14 (peak count is 21), the workload is considerably less in part because of the assumption that the departure sector does not need to space aircraft in this scenario. In addition, the longer sector flight times of the combined sector compared to the baseline reduce sector transition workload.

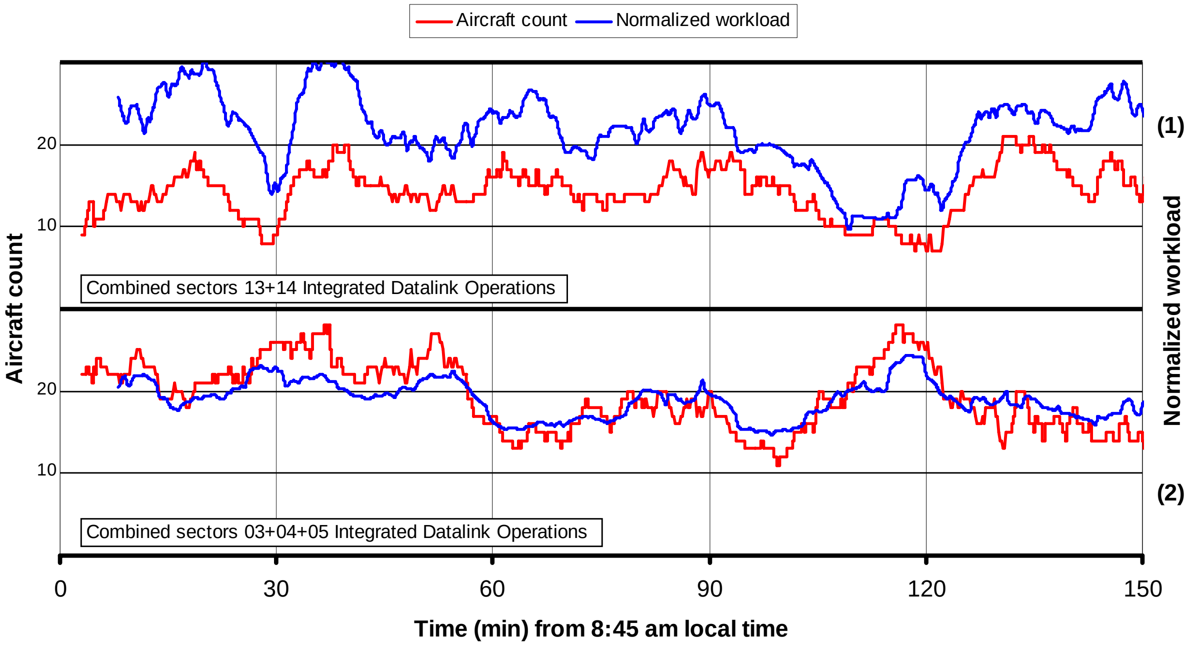

Figure 6. Aircraft count and predicted workload for Integrated Datalink Operations.

E. Predicted workload under Automated Airspace Operations

Figure 7 shows aircraft count and predicted workload for combining departure sectors 03, 04, and 05 with feeder sectors 13 and 14 as facilitated by Automated Airspace Operations. Importantly, despite combining all these sectors, the aircraft count is considerably reduced because all traffic at FL330 or above is managed by automation and not counted in the staffed airspace. The peak count is only 16 aircraft and the peak workload is moderately less than the feasible workload benchmark. Recall that SkyWest 6676 was in this staffed airspace for 8 min compared to 36 min for both Current and Integrated Datalink Operations. For this aircraft and others like it, this considerably reduces the controller's monitoring workload (i.e., the cognitive and visual components of VACM workload for detecting events such as aircraft transitioning sectors, conflicts, and spacing problems) associated with the aircraft compared to the other automation levels. In contrast, because many of the aircraft in this combined sector are in transition – either climbing or descending – and thus have short flight times through the sector, sector transition workload is a large contributor to overall workload. The workload predictions for Automated Airspace Operations suggest that it may be feasible to configure under-utilized airspace into much larger volumes when ATM automation becomes available.

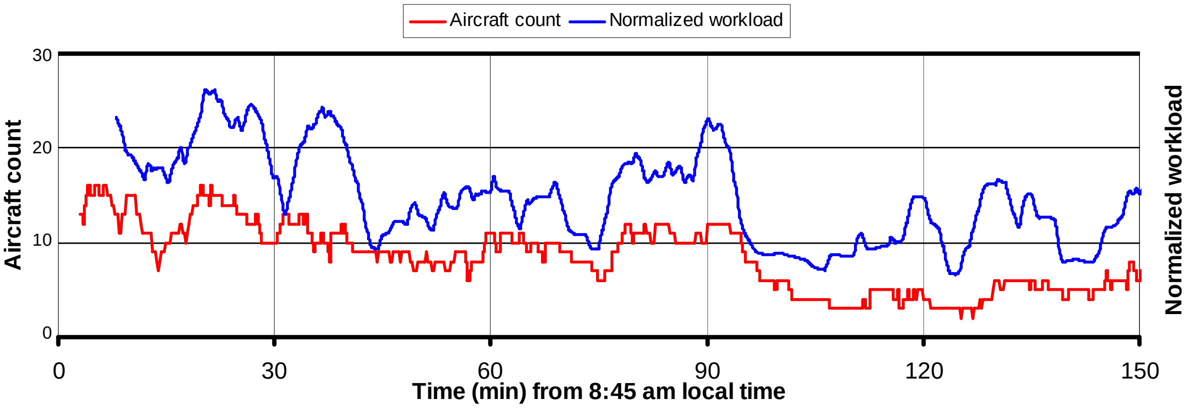

Figure 7. Aircraft count and predicted workload for Automated Airspace Operations.

V. Conclusion

Under Integrated Datalink Operations, the workload predictions suggest it is feasible to combine the high and low altitude sectors that feed the Denver TRACON, facilitating more uninterrupted descents than possible under Current Operations. Under Automated Airspace Operations, the workload predictions suggest it is feasible to combine 5 of the sectors in Area 1 of ZDV into a single staffed sector while automation provides control instructions for aircraft at FL330 and above. Lastly, care must be taken in DAC operations for airspace geometries that form shelves or other asymmetries which result in traffic flows with large variations in average sector flight time. Their impact on controller workload may not be intuitive, perhaps increasing sector transition workload beyond what is manageable. Traffic complexity equations should consider them as possible parameters.

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