Macroscopic Capacity Model with Individual Sector Closing Speed Estimates

Jerry D. Welch and John W. Andrews,
M.I.T. Lincoln Laboratory, Lexington, MA 02420-9108

Reliable airspace capacity estimates are important both for operational air traffic management and for airspace design. Air traffic management relies on manual procedures. Hence, controller workload determines the capacity of most sectors. Yet the current operational model for estimating capacity in United States airspace does not account for workload from conflict avoidance tasks. Aircraft closing speeds and airspace separation standards determine the rate of aircraft conflicts. Numerically, conflict workload intensity is the product of the conflict rate and the mean controller time required to service a conflict. As workload intensity approaches unity, the sector reaches capacity. We determine unknown model parameters by fitting capacity calculations against peak traffic observations for en route sectors. The result is an analytical model for capacity that is more accurate than the current operational model. The mean closing speed of all pairs of aircraft in a volume of airspace determines the conflict rate. This paper reports an effort to refine the conflict component of the model by replacing its original global closing speed estimate with local traffic-based closing speed estimates for individual sectors. Exact calculation of mean closing speed requires full position and velocity information for all flight tracks. The database that we used to obtain the peak traffic counts includes initial heading, speed, and altitude fields for all traffic entering a sector. Without positional coordinates and inter-sector track information, these data fields provide only crude closing speed estimates. We examined these estimates as possible indicators of sector route and altitude complexity in the New York Center. Individual sector closing speed estimates based on these observations did not improve the model fit for the 30 New York sectors.

Nomenclature

\[ G = \text{workload intensity} \]
\[ G_b = \text{background workload intensity} \]
\[ \kappa = \text{volumetric aircraft density} \]
\[ \lambda_c = \text{conflict rate} \]
\[ \lambda_r = \text{recurring rate} \]
\[ \lambda_t = \text{transit rate} \]
\[ M_h = \text{horizontal miss distance} \]
\[ M_v = \text{vertical miss distance} \]
\[ N = \text{sector aircraft count} \]
\[ N_b = \text{sector aircraft count predicted by model} \]
\[ N_p = \text{peak measured sector aircraft count} \]
\[ P = \text{recurring task period} \]
\[ Q = \text{sector volume} \]
\[ T = \text{mean transit time for sector traffic} \]
\[ \tau_c = \text{mean service time for conflict tasks} \]
\[ \tau_r = \text{mean service time for recurring tasks} \]
\[ \tau_t = \text{mean service time for transit tasks} \]
\[ V_{21} = \text{mean pair-wise closing speed of sector traffic} \]

1 Senior Staff, Surveillance Systems Group, S2-547, member.
2 Senior Staff, Surveillance Systems Group, S2-527H, non-member.
I. Introduction

Airspace capacity estimates are important both in managing air traffic and in optimizing air traffic procedures. Air traffic managers need accurate estimates of the capacity of current and reconfigured sectors to minimize delay from storms and demand peaks. When preparing for demand growth they need a means of estimating the capacity of proposed new airspace sectorization schemes and for estimating the benefits of proposed decision support tools. This paper describes a model that provides a means for addressing these needs.

Because FAA air traffic management relies on manual control procedures, controller workload determines the operational traffic limit of most sectors. The FAA’s Monitor Alert Parameter (MAP) rule is a valuable workload model for estimating the maximum safe loading for an en route sector. The MAP rule addresses controller workload caused by inter-sector coordination, which is the dominant task in large en route sectors. However, it does not account for workload from the important separation assurance task. Consequently, it can allow unrealistically high traffic densities in small sectors or in sectors where hazardous weather reduces the effective airspace volume. The MAP eighteen-aircraft maximum limit can also underestimate the true workload capacity of large sectors and merged sectors. Another limitation of the MAP model is its static definition. Workload from inter-sector coordination is inversely proportional to the mean transit time of the flights traversing the sector. Changes in traffic flow direction or flight path length can significantly change sector workload, but the MAP model does not reflect this.

We have developed a more complete analytical model for en route sector capacity which addresses these MAP deficiencies. The model can be dynamically adjusted for traffic flow changes, loss of airspace due to weather, and splitting or combining of sectors. Each en route air traffic sector has an inherent capacity determined by the aggregated workload intensity of inter-sector coordination (transit tasks), aircraft separation assurance (conflict tasks), repetitive (recurring tasks) such as traffic scanning, and activities unrelated to traffic count (background tasks). The four task types have different occurrence characteristics and dependences on traffic count. Numerically, the workload intensity associated with each of these four tasks is the product of the task rate and the mean controller time required to service the task.

The total workload intensity in a sector is a measure of the fraction of the controller’s available time required to complete all tasks. As total workload intensity approaches unity, the sector reaches capacity. We estimate the task rates from known airspace, traffic flow, and sector parameters. We infer the task service times by fitting the model to peak operational sector traffic handled by current en route air traffic sectors. The result is a formula for predicting the inherent capacity of any defined sector.

We originally inferred the service times by fitting the model’s capacity predictions against peak, clear-weather operational traffic counts from 425 sectors in the Corridor Integrated Weather System (CIWS) airspace domain in the Northeast United States. We derived the peak counts from the FAA’s Enhanced Traffic Management System (ETMS), which has relatively coarse time and spatial resolution. We introduced additional error when we under-estimated the volumes of the sectors by considering only their largest modules.

This paper describes recent progress in an effort to refine these results by using precise sector traffic observations and accurate sector volume definitions to fit all of the en route sectors in the continental United States. We obtain the peak traffic observations from the FAA Performance Data Analysis Reporting System (PDARS). PDARS instantaneous count reports are useful data sources for validating the workload capacity model. These reports provide two key pieces of information: 1) accurate peak sector counts for use in fitting the parameters of the workload model to observed traffic peaks, and 2) accurate sector transit times for estimating transit workload. The PDARS instantaneous count reports also include data fields that allow us to estimate variations in mean aircraft closing speed from sector to
sector. This has allowed us to attempt to improve the model’s conflict rate estimate by replacing its original global closing speed with sector-specific closing speed estimates.

II. The Analytical Workload Model

We model the total workload intensity in a sector as the sum of background, transit, recurring, and conflict workload intensities.

Background tasks cause a constant workload intensity $G_b$ without respect to the aircraft count in the sector. The rates of transit tasks, which occur when aircraft enter or exit the sector, and recurring tasks, which occur repeatedly for each aircraft in the sector, are both proportional to the sector traffic count. Transit tasks occur at a rate

$$\lambda_t = N/T,$$

where $N$ is the number of aircraft in the sector, and $T$ is the average transit time through the sector.

Recurring tasks occur at a rate

$$\lambda_r = N/P.$$  

Here $P$ is the mean task recurrence period per aircraft. We do not know the magnitude of the recurrence period $P$. Therefore, we perform the regression for recurring workload by fitting the dimensionless product $\tau_r/P$, which is the fraction of total time devoted to recurring tasks for each aircraft.

Conflict workload occurs when potential aircraft separation violations arise. We calculate the conflict rate for an aircraft by considering the rate at which other aircraft trajectories penetrate its protected airspace.\(^{14}\) We define $\kappa$ as the volumetric traffic density along the aircraft’s flight path, and $M_h$ and $M_v$ as the horizontal and vertical miss distances that define a separation violation. The aircraft sweeps out a volume $4M_h M_v V_{21}$ of protected airspace per unit time, where $V_{21}$ is the mean of the pair-wise closing speeds between the subject aircraft and all other closing aircraft that could pass within the defined miss distances. If the density $\kappa$ is uniform, the conflict rate is

$$\lambda_a = 4\kappa M_h M_v V_{21}.$$  

The sector controller is responsible for all aircraft in the sector. If there are $N$ aircraft in the sector each experiencing conflicts at an average rate of $\lambda_a$, then the total conflict rate for all aircraft is $N\lambda_a$. At practical traffic densities, most of these conflicts involve only two aircraft. Thus, the rate of conflicts seen by the sector controller is approximately\(^{15}\)

$$\lambda_c = N\lambda_a/2.$$  

If we define $Q$ as the sector volume, then the density of aircraft in the sector is

$$\kappa = N/Q,$$

and the sector conflict rate is approximately

$$\lambda_c = (2 \frac{N^2}{Q}) M_h M_v V_{21}.$$  

The airspace of concern for the controller can also include aircraft in contiguous sectors. Therefore, $N$ can sometimes exceed this value, and if $\lambda_a$ remains constant in the contiguous airspace, $\lambda_c$ will grow proportionally.

The complete equation for workload intensity is

$$G = G_b + \tau_t \lambda_t + \tau_r \lambda_r + \tau_c \lambda_c,$$  

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where \( \tau_t, \tau_r, \) and \( \tau_c \) are the mean service times for transit, recurring, and conflict tasks. As total workload intensity increases, it reaches a level (typically 0.8) beyond which safety begins to degrade. That intensity limit defines the sector capacity.

We determine the unknown service times by fitting them so that the model’s capacity predictions match the sector peak instantaneous counts provided by the FAA Performance Data Analysis Reporting System. PDARS uses high-resolution radar track data. It covers all airspace in the contiguous United States and provides daily reports to traffic managers in en route centers and major TRACONS. We have based this initial study on a PDARS instantaneous count report for 21 January 2007 for the New York Air Route Traffic Control Center (ZNY). We previously reported the use of sector transit time from that ZNY report to improve the accuracy of the inter-sector coordination component of the model.11

III. Objective Scoring Rule

We use an objective scoring rule for fitting the capacity model to observed peak traffic counts. We estimate values for the unknown transit, conflict, and recurring service times by regression fitting the model to the PDARS peak operational traffic count for each sector. Because the model provides a capacity upper bound, we use an asymmetric scoring rule for regression fitting. We design the scoring scheme to minimize the regression influence of sectors with peak traffic counts that are low relative to similar sectors. We assume that sectors with low peak counts are limited by lack of demand or other factors unrelated to workload. We previously used scoring parameters chosen to reward sectors whose peak counts were within plus or minus two aircraft of the bound, and we penalized only those whose peak counts exceeded the bound by more than two aircraft.11 As a result, the peak counts of many sectors exceeded the bound by more than one aircraft.

We have modified the scoring rule so that only sectors with peak counts one aircraft below the bound or equal to the bound receive positive scores. The modified rule also penalizes all sectors with peak counts greater than the bound. Specifically, sectors with counts more than one aircraft below the bound, that is those whose difference \( \Delta = N_p - N_b < -1 \), (where \( N_p \) is the peak count and \( N_b \) is the bound) receive \( \text{Score} = 0 \). Sectors with \( \Delta = -1 \) or \( \Delta = 0 \) receive \( \text{Score} = +1 \). Sectors with \( \Delta = j \), where \( j \) is any positive integer, receive \( \text{Score} = 1-2j \). This new rule increases the number of sectors with peak counts equal to the bound and further reduces the regression influence of sectors with low peak traffic counts.

IV. Estimating Mean Closing Speed

In the past, our capacity computations assumed a “global” mean closing speed \( V_{21} \) that held for all sectors. However, sectors with unidirectional flow and constant-altitude aircraft normally experience lower mean closing speeds than sectors with crossing or opposing traffic streams or with many climbing and descending aircraft. PDARS includes heading, speed, and altitude fields that allow us to estimate sector-to-sector variations in mean closing speed. These closing speed estimates have appropriate physical dimensions for direct application in the analytical capacity model. We investigated the possibility of using this information to improve the accuracy of the workload model.

Full aircraft trajectory information (position and timing) would allow us to calculate closing speeds exactly. A PDARS instantaneous count report does not include positional information, but it does provide entry and exit times, initial course, initial ground speed, and initial altitude for each aircraft entering a sector. The initial course and speed define a velocity vector for each aircraft. These velocity vectors allow one to estimate a closing speed for pairs of aircraft in the sector by assuming 1) that both aircraft flew straight, constant-speed trajectories and 2) that closest approach occurred within the sector.

Mean closing speeds computed according to the second assumption tend to over-estimate the conflict rate for aircraft pairs within the sector. With no positional information, we cannot determine whether a conflict actually occurred at closest approach. If the two aircraft occupied the sector simultaneously, but
the closest approach occurred outside of the sector, the pair either diverged within the sector (negative closing speed) or the potential conflict occurred later in a downstream sector.

We investigated different ways of conditioning these PDARS closing speed averages by time and altitude proximity. We considered two time conditions: a) average over all aircraft pairs that exited the sector within a 20-minute period following the peak daily count, and b) average over all aircraft pairs in the sector at any time in the day. We examined four altitude averaging conditions: a) aircraft pairs with initial altitudes within 2000 ft. of each other, b) aircraft pairs with initial altitudes within 3000 ft. of each other, c) aircraft pairs with initial or final altitudes within 2000 ft of each other, d) all aircraft pairs regardless of altitude.

Figure 1 shows mean closing speed estimates for the ZNY sectors using one set of conditions. Here we assigned zero closing speed to any aircraft pair that did not exit the sector in the 20-minute period following the PDARS peak count or to any aircraft pair with an initial altitude difference exceeding 2000 ft. The closing speed estimates vary significantly from sector to sector. There is little correlation between these closing speed estimates and sector size or altitude.

The average of all of the ZNY sector $V_{21}$ estimates in Figure 1 is 66.7 kt. Air traffic rules segregate traffic flow directions by altitude. Consequently, aircraft pairs with small altitude separations tend to have smaller closing speeds. Because of this, the average of the $V_{21}$ estimates grows by about 50% when we average over all aircraft pairs with initial altitude differences up to 3000 ft. The average of the $V_{21}$ estimates grows by about a factor of five when we include potential conflicts between all aircraft pairs in the sector regardless of initial altitude difference.

![Figure 1. Mean closing speed estimates from PDARS on 1/21/07. 20-minute period following peak count. Initial altitude difference <2000 ft.](image)

**V. Model Performance**

Figure 2 compares the PDARS ZNY peak sector counts for 21 January 2007 with the predictions of the fitted capacity model assuming a constant closing speed for all sectors. The chart includes twenty-seven en route ZNY sectors, with aircraft counts plotted as a function of sector volume. (We omitted the three largest ZNY sectors for plotting clarity.) Because we do not know the true magnitude of the global mean closing speed $V_{21}$, we actually perform the regression for conflict workload by fitting the product $\tau V_{21}$. This product has dimensions of distance. The regression fit for the ZNY sectors on 1/21/07 indicates that the numerical value of this conflict distance is 2.91 nautical miles. The conflict distance is essentially the mean separation distance lost while resolving each conflict. The best-fit conflict service time is $\tau = 157$ s per encounter if the closing speed $V_{21} = 66.7$ kt. If the closing speed is greater than 66.7 kt, the conflict service time is proportionally smaller.
Figure 2. Peak traffic and model values for ZNY sectors on 1/21/07. Fitted global conflict distance of 2.91 nautical miles.

Figure 3 compares the same PDARS peak count data with the predictions of the capacity model fitted using the individual sector closing speeds from Figure 1. The model fits the data significantly better in Figure 2, where we used a fixed conflict distance.

Figure 3. Peak traffic and model values for ZNY sectors on 1/21/07. Variable closing speed based on 2000 ft initial altitude differences.

The inaccuracy of the raw PDARS closing speed estimates and their large sector-to-sector variations both appear to contribute to the poor fit in Figure 3. We were able to reduce the variance of the closing speed estimates by using different combinations of time and altitude conditions. We improved the fit by
averaging over all aircraft pairs that were in the sector at any time in the day, and by averaging closing speeds for aircraft pairs with initial or final altitudes within 2000 ft of each other. Averaging over the entire day tends to reduce the variance by producing larger datasets in sectors with light traffic. However, all-day averaging gives closing speed estimates for many aircraft pairs that were not simultaneously present in the sector.

PDARS allows us to estimate altitude changes for all flights that enter other en route sectors or that enter terminal airspace within the New York center. Using both initial and final altitudes causes the effective closing speed to increase for flights that change altitude. We showed previously\(^1\) that we could improve the model’s ability to predict capacity for CWIS/ETMS sectors by increasing the effective vertical miss distance for a sector in proportion to the fraction of it flights with altitude changes. Similar adjustments occur automatically to PDARS effective closing speeds because aircraft that change altitude encounter more intruders.

We further reduced the variability by using the PDARS estimates to modulate a global conflict rate. The modulation approach applied a small additive correction to the mean closing speed to obtain a new closing speed estimate \(V_{mi}\) for each sector:

\[
V_{mi} = V_g + M(V_{si} - V_g).
\]

Here \(V_g\) is the original PDARS closing speed estimate for the \(i\)th sector, \(V_g\) is the mean of the \(V_{si}\) values for all the sectors (e.g., the 66.7 kt global closing speed from Figure 1), and \(M\) is a dimensionless constant with a value between zero and one.

Subject to the limitations of the available crude closing speed estimates, no combination of conditions provided a better fit to the observed peak traffic counts than the use of a global mean closing speed. The use of daily averages, altitude changes, and modulation all improved the fit relative to Figure 3, but did not match the fit of Figure 2. The best fit resulted when \(M\) is zero, which is the global closing speed condition. The problem appears to lie in the inaccuracy of the closing speed estimates. We would expect accurate sector-specific closing speeds to provide a better capacity fit for individual sectors.

VI. The Effects of Sector Size

The best fit occurs for small sectors (less than about 15,000 cubic nautical miles). Controller workload, not lack of demand, ultimately limits many of these small sectors. A single controller normally has full responsibility for a small sector\(^1\), and dividing the airspace into small sectors provides a balanced means of deploying additional controllers to help handle dense traffic.

Peak counts from large sectors are less useful for fitting the parameters of a workload model. Lack of demand and the MAP rule can combine to limit the peak counts in many large sectors. Figure 4, which ranks the sectors in order of increasing size, shows the difference between the MAP value and the model capacity for each ZNY sector on 1/21/07. The operational constraint of the MAP rule affects large sectors more than small sectors. No large ZNY sector had a MAP value that exceeded the limit of the capacity model. Four of the sectors exceeded their MAP values that day. ZNY34 had the highest peak count at 17 aircraft. Its MAP value was 15. ZNY09, ZNY10, and ZNY16 all had MAP values of 16, the highest in the center.

Although air traffic managers in today’s system often call upon additional controllers for assistance when large sectors experience peak loads\(^1\), the model indicates that a single controller could handle the peak workload in any of the ZNY sectors.

Sector size may help explain the success of a single global closing speed. Small sectors dominate the regression fitting process. Aircraft in small sectors spend more time near sector boundaries than do aircraft in large sectors. It follows that controllers of small sectors are likely to spend a greater fraction of their time avoiding potential conflicts with aircraft outside their sectors than are controllers of large sectors. The available data set does not allow us to identify conflicts with aircraft in adjacent sectors.
Consequently, our crude closing speed estimate for an individual sector becomes even less reliable as the size of the sector decreases.

![Graph showing ZNY sectors rank ordered by increasing volume with differences between MAP value and model capacity (Nb) for each ZNY sector. The sectors appear in order of increasing airspace volume Q.](image)

Figure 4. Difference between MAP value and model capacity (Nb) for each ZNY sector. The sectors appear in order of increasing airspace volume Q.

Notwithstanding traffic management efforts to minimize the possibility of conflicts in operational sectors, significant conflict workload occurs in small sectors. We have verified this by attempting to fit peak traffic counts to the workload model without including a conflict component. The result is a marked degradation in the fit. We can quantify the relative significance of conflict workload by using the model to compute the individual workload intensity components that would result for each ZNY en route sector if it were operating at capacity.

Figure 5 is a plot of the transit workload intensity and conflict workload intensity components for the ZNY sectors when operating at capacity. These workload components have complementary trends because, at capacity, the workload equation is a fixed-sum calculation.

The scatter in Figure 5 results from sector-to-sector variations in mean transit time. Transit workload tends to dominate in sectors larger than about 8,000 cubic nautical miles. In smaller sectors, high traffic densities generally cause conflict workload to dominate. One exception is ZNY27, which we have labeled separately in Figure 5, and which is an example of how temporary changes in traffic flow direction or flight path length can significantly alter the transit time. ZNY27 has a sector volume of 4,125 nm³ and a transit workload intensity at capacity of 0.31. This was the largest transit workload intensity in the NY Center on that day. It resulted from the relatively short (3.4-minute) average transit time of the flights through the sector in the 20 minute period following the peak count.
One goal of this work is to provide air traffic managers with information for estimating the capacity of any sector based on global parameters for the local airspace. Fitting to PDARS peak traffic counts provides numerical values for unknown parameters such as services times and the conflict distance. The only remaining sector-specific parameters necessary for computing capacity are $T$, the mean sector transit time in seconds, and $Q$, the sector volume in cubic nautical miles. Given $T$ and $Q$, the fitted model estimate for the instantaneous peak aircraft capacity $N_b$ of each of the 30 ZNY sectors based on the 21 January 2007 PDARS data, is a quadratic equation solution

$$N_b = \frac{-b + \sqrt{b^2 - 4ac}}{2a},$$

where $a = 6.8/Q$, $b = (6.8/Q + 0.025 + 7/T)$, and $c = -0.7$.

As previously noted, the best fit resulted when we computed $T$ as the average of the sector transit times of all aircraft that left the sector in the 20 minutes following the time of the peak count. (We also obtained good fits by averaging transit times over the busiest hour or half hour in each sector.) We based the sector volume on the FAA Sector Design and Analysis Tool (SDAT) coordinates of the sector on the date of the measurement, with the exception that our sector ceiling is the maximum flight altitude reported by PDARS in that sector on that day.

Figure 6 uses Eqn. 9 to generate a set of design curves for sector capacity versus sector volume with mean sector transit time as a parameter. The mean transit times for the ZNY sectors in the 20-minute periods following the peak traffic events ranged from 3.4 minutes to 32 minutes. The overall mean transit time was 11 minutes. As a general rule, sensitivity to transit time increases in large sectors, and sensitivity to volume increases in small sectors.
Figure 6. Model Capacity for ZNY Sectors as a Function of Sector Volume \( Q \) and Mean Transit Time \( T \).

Table 1 summarizes the values of the global constants used in the model for the ZNY sectors. These global constants determine the values of \( a, b \), and \( c \) in Equation 9.

Table 1. Global Capacity Model Constants for ZNY Sectors.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Value</th>
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<tbody>
<tr>
<td>( G_b )</td>
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<tr>
<td>( \tau_c )</td>
<td>157 s</td>
</tr>
<tr>
<td>( \tau_r )</td>
<td>15 s</td>
</tr>
<tr>
<td>( \tau_t )</td>
<td>7 s</td>
</tr>
<tr>
<td>( P )</td>
<td>600 s</td>
</tr>
<tr>
<td>( M_h )</td>
<td>7 nautical miles</td>
</tr>
<tr>
<td>( M_v )</td>
<td>1000 ft</td>
</tr>
<tr>
<td>( V_{21} )</td>
<td>67.7 kt</td>
</tr>
<tr>
<td>( \tau V_{21} )</td>
<td>2.91 nautical miles</td>
</tr>
<tr>
<td>( \tau_r/P )</td>
<td>0.025</td>
</tr>
</tbody>
</table>

VIII. Conclusion

We determined the unknown parameters of the model by fitting its capacity predictions against instantaneous count reports provided by the FAA Performance Data Analysis Reporting System. We based this fit on a PDARS instantaneous count report for 21 January 2007 for the New York Air Route Traffic Control Center. The focus on ZNY is informative. The New York Center has varied airspace with a wide range of sector sizes and altitudes. Many low altitude sectors in ZNY operate close to capacity because the airspace is complex and includes interactions with major airports.

The operational effect of the MAP rule and lack of demand combine to limit the peak observed counts in most large sectors. The best workload fit occurs for small sectors. The operational effect of the MAP rule has no bearing on most of the small ZNY sectors since the rule considers only inter-sector coordination workload and its traffic limit consistently exceeds the peak counts of the smaller sectors. Lack of demand does not appear to limit the peak traffic in many of the small ZNY sectors because their peak traffic counts conform closely to the capacity predictions of the workload model. Extrapolation of these predictions to larger sectors indicates that even the eighteen-aircraft MAP limit (which was never reached on 1/21/07) sometimes underestimates the inherent sector capacity.
We found that, for the 30 ZNY sectors on 21 January 2007, none of our efforts to estimate sector-specific closing speeds provided a better fit to the peak data than the use of a global mean closing speed. This result has both practical and operational implications. Practically, it means there is little value in attempting to use crude estimates of closing speed based solely on initial speed and heading. However, it does not rule out sector-specific corrections based on accurate closing speed estimates, nor vertical miss distance corrections based on counts of aircraft with vertical rates, which proved successful previously. Operationally, it reminds us that the process of structuring flow to avoid conflicts in adjacent sectors contributes to workload.

IX. Acknowledgement

This work is sponsored by the Federal Aviation Administration under Air Force Contract #FA8721-05-C-0002. Opinions, interpretations, recommendations, and conclusions are those of the authors and are not necessarily endorsed by the United States Government.

X. References

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