

SIMPLIFIED DYNAMIC DENSITY BASED CAPACITY ESTIMATION

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Abstract

Methods for estimating constant and variable sector capacity based on an airspace complexity metric, simplified dynamic density, are proposed. Simplified dynamic density is a weighted sum of seven traffic components that contribute to airspace complexity. Constant and variable estimates of maximum sector capacity, based on projected flight tracks, are used to constrain the traffic demand in fast-time simulations. Delays and aircraft counts resulting from these methods are compared with those obtained using the capacities in the current system and based on the “5/3 of average sector flight time” rule. Results show that the simplified dynamic density based capacities produce lower system-wide delays and more throughputs, and indicate more predictable air traffic demands during the peak traffic period.

I. Introduction

Air traffic demand is moderated in order to prevent congestion in sectors, which are regions within the airspace, from exceeding their capacity. This, however, leads to delays [1]. Sector capacity in the current air traffic system is based on average flight time and human judgment of sector complexity [2]. Since the flight time only partially accounts for traffic pattern, it is a partial measure of workload. In addition, the human judgment is based on past experience and is difficult to use for prediction. As a result, traffic in sectors is over and under constrained.

The sector capacity rule of “5/3 of average flight time” has been used to estimate capacity sector boundaries [3-5]. The capacity rule is based on the flight time without regard to judgment. As a result, the cognitive aspects of controller workload are not reflected.

Simplified dynamic density [6] is a weighted sum of seven traffic components that contribute to the airspace complexity. It measures workload and accounts for traffic pattern, and is suitable for various operational concepts and airspace designs.

In this paper, methods based on simplified dynamic density are purposed for estimating constant and variable sector capacity in terms of maximum number of aircraft in a fifteen-minute period. These methods estimate capacity based on changes in the traffic density and traffic patterns. The methods would be useful in a future air traffic system where sector boundaries are changing more often. Delays and aircraft counts resulting from these methods are compared with those obtained using the capacities in the current system and based on the 5/3 rule.

The sector capacity estimation methods are described in Section II. Section III presents the simulation setup. Results are discussed in Section IV. Applications of the simplified dynamic density based methods and algorithm enhancements are outlined in Section V. Finally, conclusions are presented in Section VI.

II. Capacity Estimation Methods

The baseline, the constant and the variable capacity estimation methods are discussed in this section.

1. *Published MAP (Baseline)*

Sector capacity value that is used for managing demand is known as the Monitor Alert Parameter (MAP). MAP is defined as the maximum number of aircraft in a 15-minute time period. The specified MAP values of the sectors have been used for generating baseline values of delays and aircraft counts using Airspace Concept Evaluation System (ACES) [7] simulations. These capacity values are initialized at startup and remain constant throughout the simulation.

2. *Constant Design MAP (CDM)*

Table 1 lists the average sector flight times and the corresponding MAP values following the Federal Aviation Administration’s (FAA) sector design guidelines [2]. Observe that the MAP values are

between a minimum of 5 and a maximum of 18 aircraft.

Table 1. Design MAP Values

Average Sector Flight Time (min)	MAP Value
3	5
4	7
5	8
6	10
7	12
8	13
9	15
10	17
11	18
12 or greater	18

The numerical values listed in Table 1, which we call Design MAP values, are based on the “5/3 of average flight time” rule, which is

$$MAP_{design}(S) = \min \left\{ \max \left\{ 5, \left\lfloor \frac{5}{3} \cdot T_f + \frac{1}{2} \right\rfloor \right\}, 18 \right\}$$

where T_f is the average flight time in sector S .

In this method, high-altitude sector capacities are computed by applying the 5/3 rule to the average sector flight times from the Baseline simulation. These capacities are initialized at startup and remain fixed for the simulation’s duration.

3. Constant SDD-Based MAP (CSM)

The SDD value for a sector is defined as a weighted sum of seven traffic dependent metrics, which are listed in Table 2, in 15-minute time-period T [8]:

$$SDD(S, T) = \sum_{1 \leq i \leq 7} w_i \cdot c_i$$

where w_i is the weight associated with the traffic dependent metric c_i .

Note that the traffic dependent metrics are computed on traffic accumulated over a fifteen-minute period. The numerical values listed in Table 2 are from human-in-the-loop experiments [8]. Although these weights were derived from analysis of results from a generic airspace, we have used them

in all high-altitude sectors in the 20 Air Route Traffic Control Centers in the U. S. It is quite possible that weights might be different for sectors in each center; therefore, this is a limitation of the present study.

Table 2. SDD Weights and Threshold

Metric		Value
Occupancy counts	w_1	2.2
Altitude changes	w_2	0.2
Proximities	w_3	1.2
Sector boundary crossing	w_4	0.4
Heading variance	w_5	0.0005
Speed variance	w_6	0.0005
Traffic density	w_7	30000
Threshold		70

The workload in a sector is assumed to have exceeded safe limits when its SDD value is above 70. 70 is for peak traffic during a good weather day [8]. The threshold value is used for assigning values to a binary variable $LL(S, T)$, which is defined as

$$LL(S, T) = \begin{cases} 1 & \text{if } SDD(S, T) \leq \text{threshold}; \\ 0 & \text{if } SDD(S, T) > \text{threshold}. \end{cases}$$

A value of one indicates that the sector workload would be at or below the acceptable workload level, while a value of zero indicates that the workload level would be exceeded, for the 15-minute time interval.

Defining the peak traffic count in a 15-minute time interval as

$$ac(S, T) = \max_{1 \leq i \leq 15} \{count(S, t_i)\}$$

where t_i is the i -th minute in the 15-minute time interval T . The peak traffic count in the sector such that its workload would not be exceeded is

$$ac_{SDD}(S) = \max_{1 \leq j \leq 96} \{5, LL(S, T_j) \cdot ac(S, T_j)\}$$

where the index j represents the 96, 15-minute intervals in the 24-hour period of the day, and 5 is the minimum value to reflect the lower bound of the MAP values in current air traffic system.

In case the workload in a sector always exceeds the acceptable workload level in the entire 24-hour period of the day, the published MAP of the sector will be used. The MAP value based on SDD is

$$MAP_{SDD}(S) = \begin{cases} ac_{SDD}(S) & \text{if } \exists T_j : LL(S, T_j) = 1; \\ PM(S) & \text{if } \forall T_j : LL(S, T_j) = 0 \end{cases}$$

where $PM(S)$ denotes the published MAP of sector S . This MAP value, computed using the traffic data from the Baseline simulation, is set as the constant capacity for the entire day.

An example of MAP value computation following the procedure discussed above is illustrated via Figures 1 and 2. Figure 1 shows the SDD values of Sector 67 in Cleveland Center (ZOB67) over the 24-hour period and the threshold value of 70. Figure 2 shows the traffic count as a function of time; the green region (marked with vertical lines) marks the times when the SDD values are below the threshold marked in Figure 1. Observe that the maximum number of aircraft in this region is 13 (see near 10:00 EDT location) therefore it is selected as the MAP value for Sector 67 for the 24-hour period of the day.

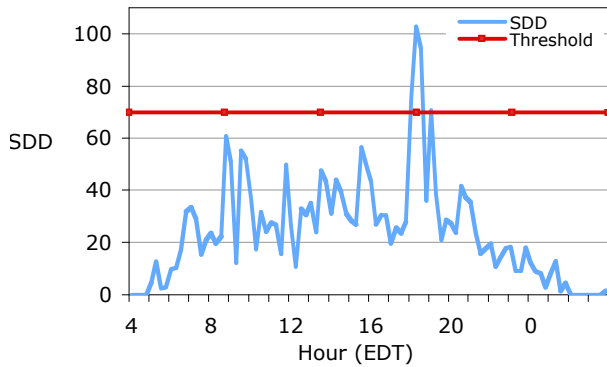


Figure 1. SDD Values in Sector 67 of the Cleveland Center

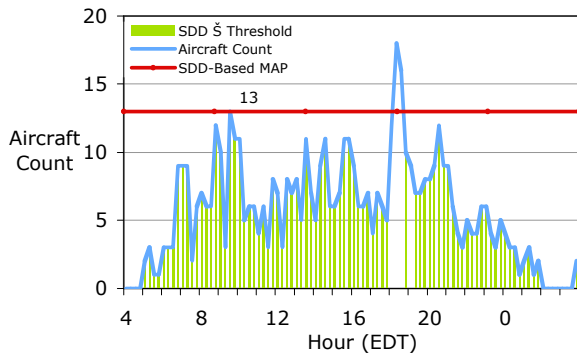


Figure 2. Traffic Counts in Sector 67 of the Cleveland Center

4. Variable Design MAP (VDM)

The central difference between the Variable Design MAP (VDM) and the CDM methods is that in the VDM method, a new MAP value is computed once every fifteen-minutes using the next six-hours of forecast traffic data. The CDM procedure discussed previously in Subsection 2 is used for computing the MAP value for each sector. These values are then specified as forecast capacities of the sectors for traffic flow management (TFM) procedure in ACES. The TFM holds back aircraft prior to departure and also during flight to ensure that the specified sector capacities and airport arrival/departure capacities are not exceeded. The control imposed by the TFM has an effect on the forecast traffic for the next six-hours; thus, the MAP values also change when they are recomputed.

5. Variable SDD-Based MAP (VSM)

This method replaces the capacity formula in the VDM method with the SDD-based capacity estimation. The following procedure is applied to compute the sector capacities individually among all high-altitude sectors.

As discussed earlier, SDD is a weighted sum of the seven air traffic components over a 15-minute time period, T , and each component value is computed from a group of flights. Therefore, given a set of flights $F = \{f_1, f_2, \dots, f_n\}$ in sector S in T , the SDD can be represented as a function of flights:

$$SDD_{sector}(T) = SDD_{flight}(F)$$

By removing a flight from F , the sector SDD decreases. The flight that causes SDD to drop the most when it is removed from F , is considered to have the highest impact on controller workload. The workload impact function is defined as

$$Impact(f) = SDD_{flight}(F) - SDD_{flight}(F \setminus \{f\})$$

where $f \in F$, and ' \setminus ' stands for the set complement operator.

With this function, flights in the same sector can be ordered by their workload impact values. During the capacity forecast, when the SDD does not exceed the threshold, the sector is not overloaded, and thus the initial published MAP value can be set as the sector capacity. On the other hand, when the SDD

exceeds the threshold, flights having the highest impact values in the forecast period are removed one by one, until the SDD no longer exceeds the threshold. If the maximum instantaneous aircraft count among the remaining flights is higher than the constant published MAP value, it will be used as the sector capacity.

Ideally, flights having the highest impact should also be the first selected for delay in the simulation so that the sector load is reduced below the threshold. However, selection of flights for delay has not been implemented in the traffic flow management module in ACES. As a result, flights having lesser impact may be delayed in the simulations.

III. Simulation Setup

This section describes the simulation setup of the study. Historical traffic data on Thursday, 21 April 2005, a good weather and high volume day, were obtained from the Aircraft Situation Display to Industry (ASDI) data. ASDI data were provided by the FAA's Enhanced Traffic Management System (ETMS).

49,315 flight schedules were extracted from the ASDI data. 2,504 of these contained invalid information, such as unknown departure or arrival airports, bad trajectory data, and aircraft types that could not be handled in ACES. These were filtered out from the simulations. The remaining 46,811 traffic schedules and flight plans (94.9% of the original data set) were simulated in ACES. Settings such as airport throughputs, sector boundaries, and wind data, remained constant among simulations. Airport capacities with maximum throughputs were obtained from the Operations and Performance Data, which were provided by FAA's Aviation System Performance Metrics (ASPM). Sector geometries were year 2005 specific. The Rapid Update Cycle wind data from the National Oceanic and Atmospheric Administration of the U.S. Department of Commerce were used.

Two variables in the settings are airport capacity and high-altitude sector capacity. Airport capacity is measured by Airport Acceptance Rate (AAR) and Airport Departure Rate (ADR). AAR and ADR are the number of arrival and departure flights, respectively, that can be handled in an airport per hour. High-altitude sector capacity is defined by the

five capacity estimation methods. The sector geometry files contain data on 466 high-altitude sectors, and 299 (64.2%) of these are at or above FL230. Figure 3 shows a cumulative frequency graph of minimum altitudes of the high-altitude sectors.

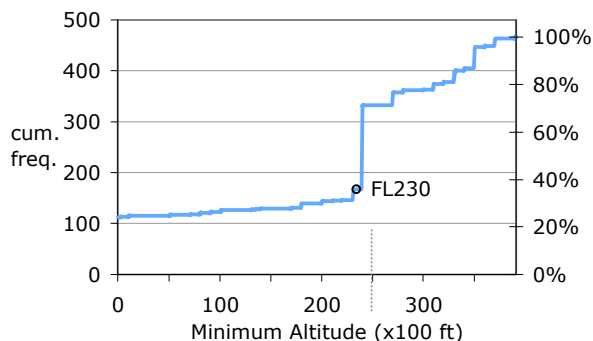


Figure 3. Cumulative Frequencies of Minimum Altitudes of High-Altitude Sectors

A total of ten simulations were run. The first five simulations used the five capacity estimation methods with unlimited AAR and ADR for the airport capacity. The last five simulations used the five capacity estimation methods with the actual AAR and ADR from the ASPM for the airport capacity.

In the Baseline and two constant capacity estimation methods (CDM and CSM), sector capacities were initialized once at startup and remained fixed during the simulation. Sector capacities were dynamically forecast and updated in the two variable capacity estimation methods (VDM and VSM).

IV. Results

The 46,811 flights were successfully simulated in ACES using the five capacity methods and two airport capacity settings. Simulation results were collected and analyzed based on three metrics: delay times, aircraft counts, and sector capacities.

1. Delay Times

Delay time of a flight, f , is determined by the time difference between actual and scheduled gate arrivals:

$$delay(f) = arrival_{actual}(f) - arrival_{scheduled}(f)$$

Statistics for delayed flights were computed from the simulation results using the (A) unlimited and (B) actual airport capacity settings (see Tables 3 and 4 respectively), and the average flight delay for each of the five methods is presented in Figures 4 and 5. According to the data, the SDD-based methods (CSM and VSM) have the least number of delayed flights and the shortest averaged delay times among the methods, regardless of which airport capacity setting is used.

Table 3. Statistics for Delayed Flights (Unlimited Airport Capacity)

(A)	No. of Delayed Flights	Average Delay (min)	Max. Delay (min)	Std. Dev. of Delay (min)
Baseline	18,500	2.59	154.60	11.83
CDM	18,760	4.15	269.07	18.72
CSM	18,128	0.36	29.19	1.38
VDM	18,853	2.71	154.31	11.54
VSM	18,234	0.74	62.37	3.29

Table 4. Statistics for Delayed Flights (Actual Airport Capacity)

(B)	No. of Delayed Flights	Average Delay (min)	Max. Delay (min)	Std. Dev. of Delay (min)
Baseline	32,120	7.48	134.73	13.27
CDM	32,234	8.98	450.55	22.41
CSM	31,995	6.38	124.33	9.62
VDM	32,242	7.42	143.69	12.96
VSM	31,998	6.83	182.87	10.08

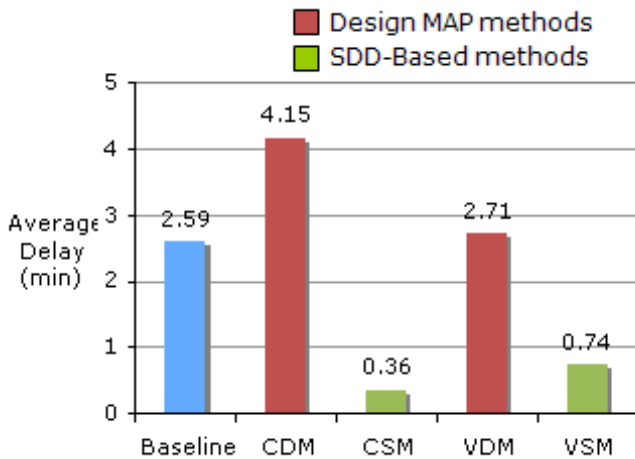


Figure 4. Average Delay among Methods (Unlimited Airport Capacity)

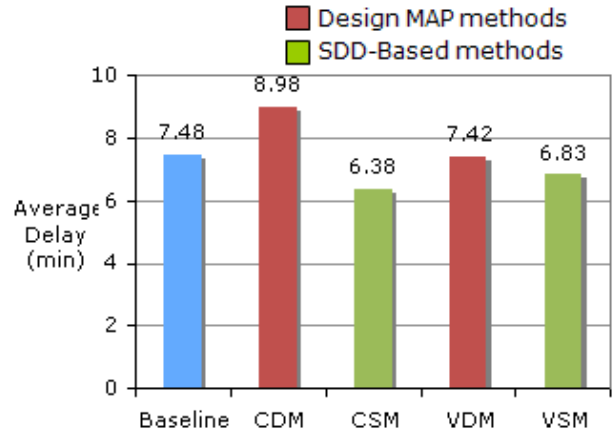


Figure 5. Average Delay among Methods (Actual Airport Capacity)

Among the constant capacity estimation methods (the Baseline, CDM and CSM), the CSM method generates the least number of delayed flights, (A) 18,128 and (B) 31,995, and the shortest average delay time, (A) 0.36 minutes and (B) 6.38 minutes.

With respect to the variable capacity estimation methods (VDM and VSM), the VSM method produces the fewest number of delayed flights, (A) 18,234 and (B) 31,998, and the shortest average delay time, (A) 0.74 minutes and (B) 6.83 minutes.

If all the methods are compared, the SDD-based methods using the unlimited airport capacity yield the smallest maximum delay times, ranging from 29.19 minutes (CSM) to 62.37 minutes (VSM), which are 18.9% and 40.3% of that of the Baseline (154.60 minutes). The two methods also produce the smallest standard deviations of delay for the delayed flights. This means that SDD-based average delay times are closer to the mean values, and thus, more predictable.

Even using the actual airport capacity, the SDD-based methods still produce the smallest standard deviations of delay for the delayed flights, ranging from 9.62 minutes (CSM) to 10.08 minutes (VSM), which are smaller than that of the Baseline (13.27 minutes).

On the other hand, the Design MAP methods (CDM and VDM) create the greatest numbers of delayed flights as well as average delay times in both airport capacity cases. This indicates that the unadjusted Design MAP formula ($5/3$ the average sector flight time) does not reflect the traffic pattern as well as the Baseline method. In fact, when the CDM method is used, there are on average (A) 4.15

minutes and (B) 8.98 minutes of delay among the delayed flights, and the maximum delays are (A) 269.07 minutes (4.5 hours) and (B) 450.55 minutes (7.5 hours). This indicates that the Design MAP is not a good capacity estimator.

The SDD-based methods (CSM and VSM) in the unlimited airport capacity case result in 86.1% (CSM) and 71.4% (VSM) improvements in the average delays over the Baseline. However, the same methods in the actual airport capacity case result in 14.7% (CSM) and 8.7% (VSM) improvements in the average delays over the Baseline. The huge difference between improvements using two different airport capacity settings indicates that airport capacity can be a potential bottleneck for current and future airspace traffic.

Figure 6 shows a distribution of the number of arrival flights among the 20 centers. Classifying delayed flights by arrival airport, the average delays of the delayed flights for each of the centers in the Baseline and constant capacity methods, and the Baseline and variable capacity methods are presented in Figures 7 and 8 (using unlimited airport capacity) and Figures 9 and 10 (using the actual airport capacity) respectively.

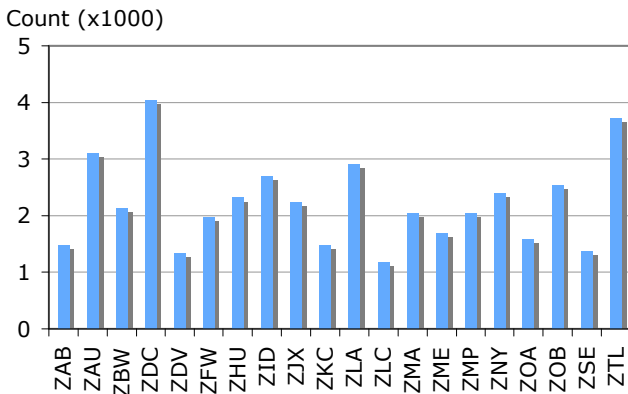


Figure 6. Distribution of the Number of Arrival Flights among Centers

In the unlimited airport capacity case (Figures 7 and 8), using the SDD-based methods yield reductions in average delays in all the centers.

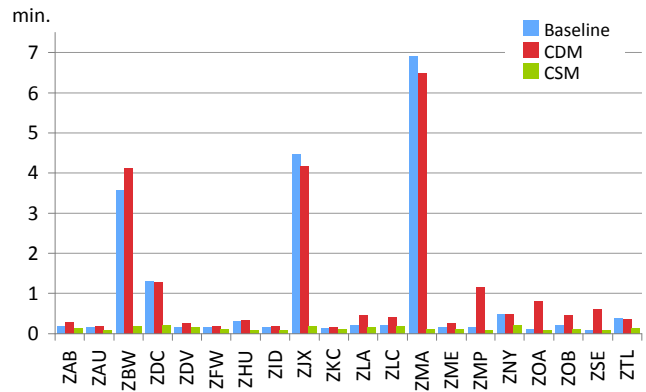


Figure 7. Average Delays among Centers (Constant Capacity Methods, Unlimited Airport Capacity)

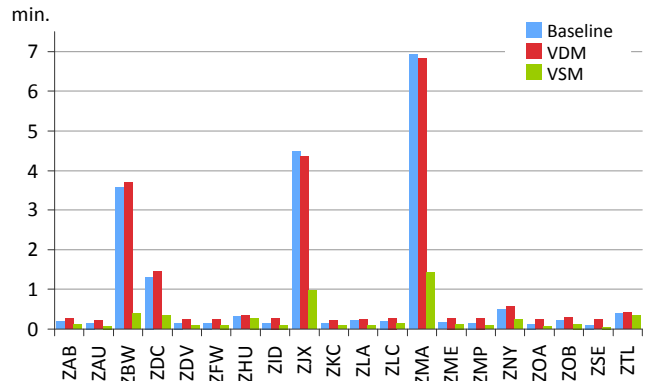


Figure 8. Average Delays among Centers (Variable Capacity Methods, Unlimited Airport Capacity)

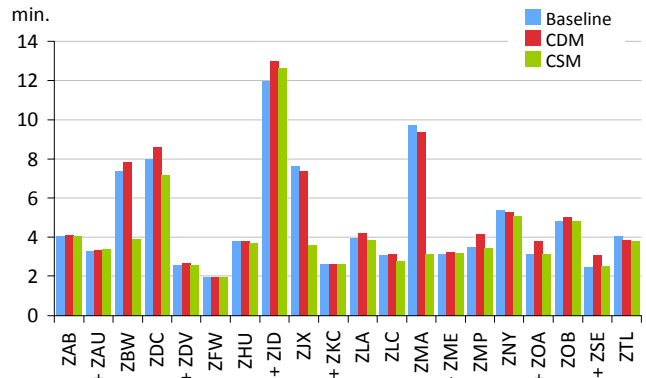


Figure 9. Average Delays among Centers (Constant Capacity Methods, Actual Airport Capacity)

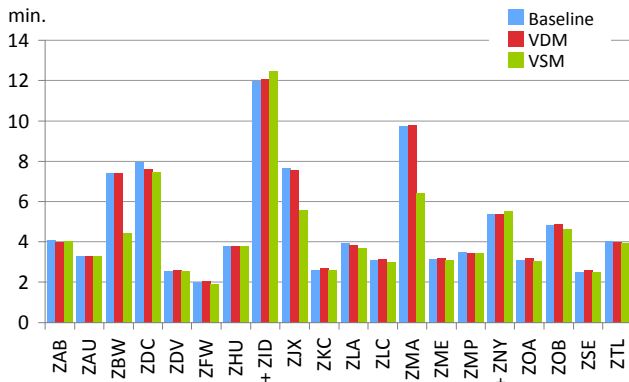


Figure 10. Average Delays among Centers (Variable Capacity Methods, Actual Airport Capacity)

In a comparison between the SDD-based methods and the Baseline using actual airport capacity, the SDD-based methods reduce average delays in thirteen centers (CSM) and eighteen centers (VSM) respectively. For the centers gaining average delays, their names are prefixed with ‘+’ signs.

Finally, Table 5 lists the top four centers, Miami Center (ZMA), Jacksonville Center (ZJX), Boston Center (ZBW) and Washington Center (ZDC), and their average delay time reductions when SDD-based methods are used over the Baseline.

Table 5. Average Delay Improvement to the Baseline Using SDD-Based Methods

	Unlimited Airport Capacity		Actual Airport Capacity	
	CSM	VSM	CSM	VSM
ZMA	6.8 min.	5.5 min.	6.6 min.	3.3 min.
ZJX	4.3 min.	3.5 min.	4.1 min.	2.1 min.
ZBW	3.4 min.	3.2 min.	3.5 min.	3.0 min.
ZDC	1.1 min.	1.0 min.	0.9 min.	0.5 min.

2. Aircraft Counts

Figure 11 shows aircraft counts over time from the Baseline and two constant capacity estimation methods (CDM and CSM) in Boston Center (ZBW) in the actual airport capacity case. According to the figure, the peak traffic period is between 16:00 EDT and 20:00 EDT on 21 April 2005. Observe that the aircraft-count curve of the CDM method stays below the other two curves during the peak traffic period. It then stays above the other two curves after 22 April 2005 00:00 EDT.

The cumulative sum of the differences in the aircraft counts between the two methods and the Baseline are presented in Figure 12. When comparing the Baseline, the CSM method estimates more capacity as the peak cumulative throughput difference is 75 aircraft at 21 April 2005 20:30 EDT. On the other hand, the lowest cumulative throughput difference of the CDM method is -238 aircraft at 21 April 2005 23:30 EDT.

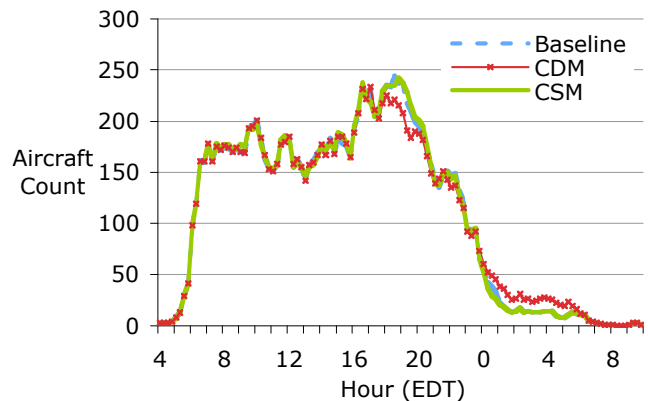


Figure 11. Throughputs in Boston Center

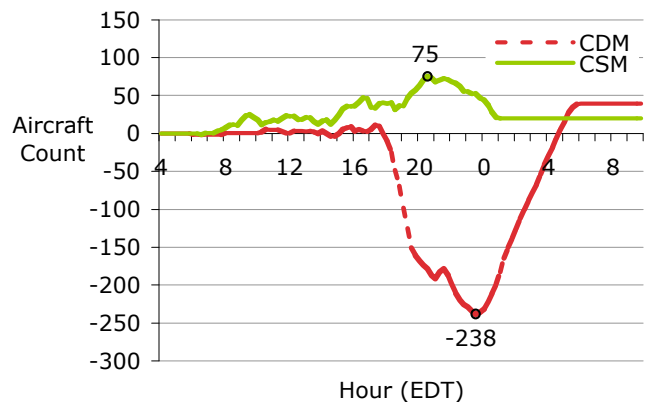


Figure 12. Cumulative Sum of Throughput Differences to the Baseline in Boston Center

Both Figures 11 and 12 shows that the CSM method can handle air traffic demand during the peak traffic period. The figures also reveal that in the CDM method, flights are delayed during the peak traffic period due to over-constrained sectors in Boston Center during 21 April 2005. As mentioned earlier, traffic in a sector is constrained in order to prevent too much workload. However, an over-constrained sector cannot provide enough capacity during a peak traffic period. As a result, flights are delayed. The aircraft count metric explains why the CDM method produces more delayed flights, longer

average delay time, higher maximum delay time, and larger standard deviation values.

3. Sector Capacities

Figure 13 shows a distribution of the capacities of the high-altitude sectors among the Baseline and the two constant capacity methods (CDM and CSM) in the unlimited airport capacity case. In the Baseline, sector capacities range from 9 to 25 and most sectors have capacities 15, 18 and 20. However, most sectors in the CDM method have capacities 5, 12 and 18. This indicates that the upper bound value, 18, in the capacity formula under-assigns capacity of some sectors. In fact, sector capacities in the CSM method range from 5 to 26 and most sectors have capacities between 13 and 15.

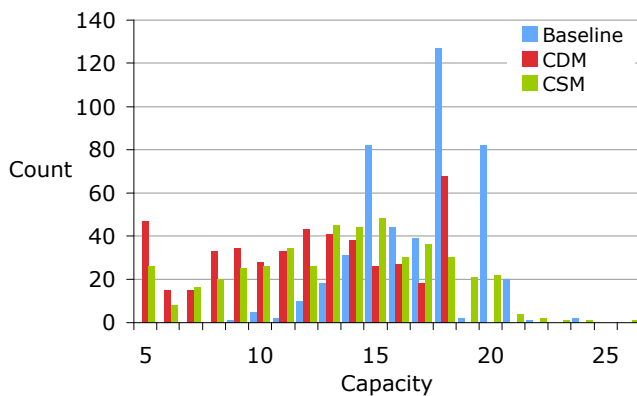


Figure 13. High-Altitude Sector Capacity Counts

A ratio of peak demand to sector capacity (D/C) represents a balance between demand and capacity of a sector during the peak load period. A D/C ratio equal to 1.0 indicates that sector capacity matches the peak traffic count. A D/C ratio less than 1.0 indicates that more capacity than the demand needed is assigned. On the contrary, a D/C ratio greater than 1.0 indicates that less capacity than the demand needed is assigned. The distribution graph of the D/C ratios among the Baseline, CDM and CSM methods in the unlimited airport capacity case is shown in Figure 14.

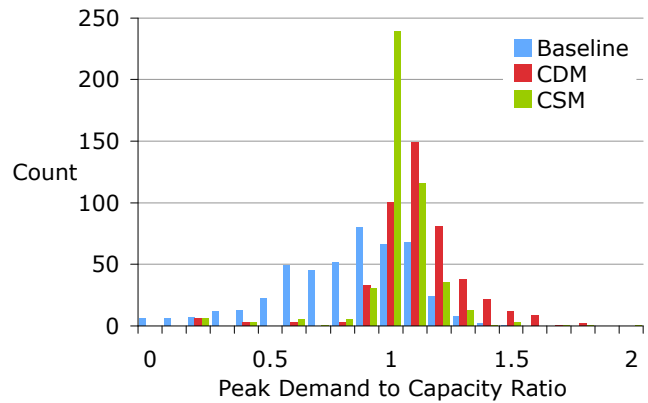


Figure 14. Sector Counts of Peak Demand to Capacity Ratios

The mean D/C ratios of the three methods are 0.83 (Baseline), 1.11 (CDM) and 1.03 (CSM) respectively. As 0.83 is less than 1.0, more capacity than the demand needed is assigned in the Baseline. On the other hand, 1.11 is greater than 1.0, less capacity than the demand needed is assigned in the CDM method. Since the D/C ratio of the CSM method is the closest to 1.0, this method produces the best sector capacity assignments among the three methods. In addition, the standard deviations of the D/C ratios among the three methods are 0.27, 0.21 and 0.16 respectively. The CSM method produces the most predictable balance between demand and capacity during the peak traffic period.

Figure 15 shows the cumulative frequency graph of the capacities of the high-altitude sectors among the Baseline, CDM and CSM methods. The Baseline curve stays to the right of the other curves indicating that higher sector capacities are allocated when the published MAP is used. Thus, the Baseline published MAP values are over-assigned. Though the CDM method allocates the lowest sector capacities, based on the delay statistics in Tables 3 and 4, some sector capacities are under-assigned in this method. Finally, the CSM method allocates capacities lying between the two methods and produces the smallest average delay time.

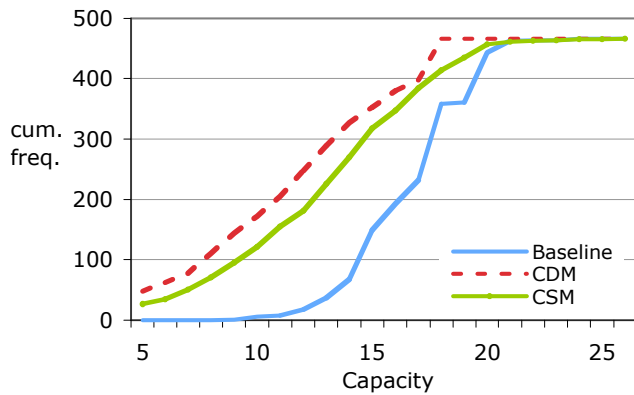


Figure 15. Cumulative Frequencies of High-Altitude Sector Capacities

Figures 16 and 17 present capacities in two sectors, Sector 37 in Washington Center (ZDC37) and Sector 39 in New York Center (ZNY39), over time for the Baseline and the two variable capacity estimation methods (VDM and VSM). In addition, the aircraft counts in these sectors are shown as demands. In Figure 16, capacities estimated from the VDM method during the peak-load period are generally higher than the demand and capacities from the Baseline and VSM methods. However, in Figure 17, the capacities generated from the VDM method never exceed the Baseline and VSM capacities. In fact, the VDM method cannot provide enough capacity to handle the demand during the peak-load period. This indicates that the Design MAP capacity formula ($5/3$ the average sector flight time) can over-estimate capacity in some sectors, and under-estimate capacity in others.

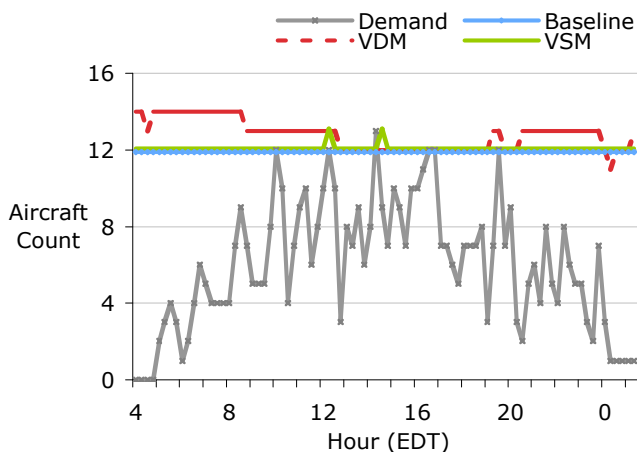


Figure 16. Demand and Capacities of Sector 37 of the Washington Center

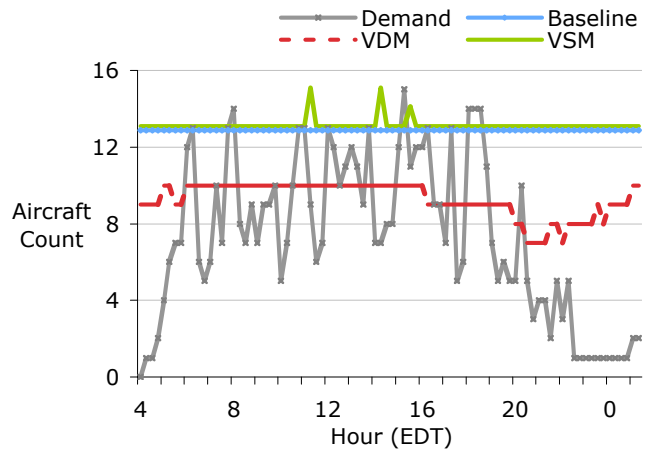


Figure 17. Demand and Capacities of Sector 39 of the New York Center

V. Applications and Enhancements

Based on the results discussed above, sector capacities based on SDD-based capacity estimations can be assigned more predictably due to workload adjustments made from the air traffic components. The SDD-based MAP can be a better indicator of forecasted sector load. In this case, the traffic management unit can have more detailed information, such as predicted high sector-load periods and an ordered list of flights having the highest impact on the controllers, and adjust and balance traffic flows accordingly.

The SDD-based constant capacity estimation can also be used as a guideline to assign sector capacities for new dynamic airspace designs. For a new airspace design, a simulation with unconstrained sector capacity can be run. Aircraft counts and SDD values can be collected from the simulation results. By using the CSM method, the capacity of individual sectors can be computed.

Future work will begin to focus on enhancing the traffic flow management module in ACES to selectively delay flights that have the highest impact on controllers. The initial capacities of the CSM methods will be extended so that the capacity estimator does not rely on the published MAP. It will also be interesting to combine both the CSM and VSM methods to form a hybrid model, such that the sector capacity can be dynamically estimated every four to six hours or during different peak-load periods, instead of fifteen-minute periods.

VI. Conclusions

Five capacity estimation methods – the Baseline, constant and variable methods based on 5/3 rule, and constant and variable methods based on simplified dynamic density – were simulated in Airspace Concept Evaluation System using historical traffic schedules with the unlimited and actual airport capacity. The sector capacity formula used in the 5/3 rule is based on average flight time, which does not include capacity adjustments based on human judgment. Fixed capacities are used in the Baseline and two constant capacity methods, and variable capacity estimations are applied in the two variable capacity methods. Results based on the delays, aircraft counts and sector capacities were reported and analyzed.

Results show that capacity estimations using the 5/3 rule produce longer average delays and lower sector throughputs compared to the other methods. In addition, the variable 5/3 rule as well as the baseline constant published capacities underestimates sector capacity in some centers. Due to the lack of traffic complexity in the 5/3 rule, it is impractical to estimate capacities simply based on such a capacity formula.

Results also show that simplified dynamic density based methods produce the shortest average delay time. The constant method does not over-assign (as does the Baseline method) or under-assign (as does the 5/3 rule). In the variable method, capacities can be adjusted dynamically, according to the traffic demand. Based on these positive results, simplified dynamic density based capacity estimates have the potential to improve the accuracy of benefit assessment for dynamic airspace designs.

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