Dynamic Density – A Review of Proposed Variables

NAS Advanced Concepts Branch, ACT-540
William J. Hughes Technical Center
Federal Aviation Administration

March 22, 2000

Version 1

Introduction

The term Dynamic Density (DD) originated in the RTCA Task Force 3 report. The report describes the DD as "the essential factors affecting conflict rate in both en route and terminal airspace." These factors are traffic density, complexity of flow and separation standards. The calculation and prediction of DD has been identified as a key need for assessing workload of future traffic (RTCA Task Force 3 Free Flight Implementation Report, 1995).

DD is also defined as air traffic control (ATC) taskload and is the basis of controller subjective workload. DD is analogous to air traffic complexity or difficulty of a situation. DD is "a measure of control-related workload that is a function of the number of aircraft and the complexity of traffic patterns in a volume of airspace" (Laudeman, Brasil, & Branstrom, 1996).

Although the term Dynamic Density is relatively new, the factors that contribute to the sector level traffic complexity has been of interest to researchers for a long time. In a literature review of sector complexity, Mogford, Guttman, Morrow, and Kopardekar (1995) identified and reviewed air traffic complexity related literature since 1963. Most articles reviewed in this technical note identify that aircraft count, sector geometry, traffic flows, separation standard, aircraft performance characteristics, weather are the most common factors that contribute to the air traffic complexity or difficulty. The following is a list of the factors that contribute to the air traffic complexity:

1. Number of aircraft
2. Aircraft density or traffic volume
3. Aircraft handled in prior time interval (e.g., last hour)
4. Number of arrivals
5. Number of departures
6. Number of emergencies
7. Number of special flights
8. Coordination
9. Traffic mixture (arrivals, departures, and over flights)
10. Number of airport terminals
11. Traffic distribution
12. Staffing
13. Weather conditions
14. Equipment status
15. Number of communications with aircraft
16. Number of communications with other sectors
17. Presence of conflicts
18. Number of path changes
19. Preventing conflicts (crossing or overtake)
20. Number of handoffs and printouts
21. Handling pilot requests
22. Traffic flow structure

23. Clustering of aircraft
24. Control adjustments involved in merging and spacing
25. Mixture of aircraft types
26. Combing and descending aircraft flight plans
27. Number of intersecting flight paths
28. Number of required procedures
29. Number of military flights
30. Airline hub location
31. Weather and its severity
32. Aircraft routing
33. Special use airspace
34. Sector geometry
35. Sector size
36. Requirements for longitudinal and lateral spacing
37. Radar coverage
38. Frequency congestion
39. Number of altitudes used
40. Others

As identified above, there are a number of factors that contribute to the complexity. Therefore, researchers have been interested in examining how the effect of these factors on complexity can be measured using variables. Since 1995, there have been multiple exploratory studies that were aimed at identifying the variables that contribute to DD. The most notable include NASA, Wyndemere, and FAA WJHTC studies. These separate studies have included initial examination of DD variables.

Objective

The objective of this report is to document different DD variables and their relationships. The report does not attempt to validate these variables.

This report is expected to provide a unified review of DD variables to date. This report is intended for researchers interested in investigating DD or air traffic complexity. This document is also expected to be a working document. As more DD variables are developed or validated, this document will be updated.

A complexity factor is defined as the reason that contributes to the complexity whereas a variable is defined as the measurement of the contribution of one or more factors to the complexity. Generally, factors are observable but may or may not be directly measurable (e.g., weather, arrival rate) where as variables are measurable (e.g., aircraft count, arrival rate).

The following pages provide different dynamic density metrics as developed and reported by various researchers.

Dynamic Density Variables

ID	Variable Name	Description	Purpose
1	*Kopardekar, P., and DiMeo, K, 1997, Dynamic Density Variables, PowerPoint Briefing.*		
1.1	Aircraft density (AD)	Number of aircraft divided by the airspace volume. See formula. [1] $AD = \frac{Number\ of\ Aircraft}{Airspace\ Volume}$	Capture the monitoring taskload.
1.2	Convergence recognition index (CRI)	Based on how close the angle of convergence is to the shallow convergence of 30 ^{0}. See formula. [1] $CRI = \sum \left(7 - \frac{Adjusted\ Convergence\ Angle}{30}\right)^2$	Capture the degree of difficulty in recognizing shallow convergence angles.
1.3	Separation criticality index (SCI)	Based on how close the separation between the two aircraft will be in relation to the separation minima. See Formula. [1] $SCI = \sum (3 - SI)^2$ $Separation\ Index\ Longitudinal\ (SILO) = \frac{\Delta Y}{Logitudinal\ Minima}$ $Separation\ Index\ Lateral\ (SILA) = \frac{\Delta X}{Lateral\ Minima}$ $Separation\ Index\ Horizontal\ (SIH) = \frac{\sqrt{\Delta X^2 + \Delta Y^2}}{Lateral\ Minima}$ *En Route and Terminal* $Separation\ Index\ (SI) = \frac{SIV + SIH}{2}$	Capture the monitoring and decision making taskload associated with examining separation criticality. Include if *SIH < 4, SIV < 2, and SI < 3.*

ID	Variable Name	Description	Purpose
1.4	Degrees of freedom index (DOFI)	Based on how many options the controller has to move the aircraft that are in a potential conflict situation. See Formula. [1] $DOFI = \sum (12 - Available\ DOF\ per\ pair)^2$ *DOF = Degrees of Freedom*	Capture the degree of difficulty in developing resolution strategies for conflict pair. Fewer the options, the higher the difficulty.
1.5	Coordination taskload index (CTI)	Based on how close the aircraft is to the sector boundary that is not handed off to the next sector. See Formula. [1] $CTI = \sum \left[\frac{1}{Time\ to\ reach\ CCP + (Time\ to\ reach\ SB - Time\ to\ reach\ CCP)^2} \right]$ $CTI = \sum [10 - Time\ to\ reach\ Sector\ Boundary]^2$ CCP = Coordination Completion Point, a point at which facility procedures require that coordination must be completed (e.g., 2.5 miles from sector boundary).	Capture the taskload associated with the coordination. The larger the distance from the sector boundary, the lower the urgency for hand-off and lower the taskload. Smaller the distance from the sector boundary, higher the urgency for hand-off and higher the taskload. All aircraft, which are 10 minutes or less from CCP are included.
2	*Breitler, A., L, Lesko, M. J., Kirk, K. M., 1996, Effects of Sector Complexity and Controller Experience on Probability of Operational Errors in Air Route Traffic, CAN Corporation, Task 9, FAA Contract DTFA01-95-C-00002.*		
2.1	Operationally acceptable level of traffic (OALT)	Maximum number of aircraft in a sector that a controller can manage effectively during a defined time period. [2]	Rule of thumb based on number of aircraft. This is the ETMS alert parameter. A static variable. Correlation with operational errors (r = - 0.06, N.S.)
2.2	Maximum instantaneous aircraft (MIAC)	Maximum number of aircraft that a controller should ever have to manage in the sector during a defined time interval (60 minutes). [2]	Similar to OALT but based on time period. Static parameter. Correlation with operational errors (r = - 0.104, N.S.)
2.3	Ease of vectoring	Subjecting rating by each center (from 1 to 5). [2]	ARTCC wide vectoring ease. Static parameter. Correlation with operational errors (r =

ID	Variable Name	Description	Purpose
			0.184, S.)
2.4	Ease of transitioning	Subjective rating by each center (from 1 to 5). [2]	ARTCC wide transitioning ease. Static parameter. Correlation with operational errors (r = 0.231, S.)
2.5	Number of sides	Number of sides for each sector. [2]	Sector geometry related difficulty. Static parameter. Correlation with operational errors (r = 0.094, N.S.)
2.6	Number of main jetways	Number of main jet routes through each sector. [2]	Capture sector flow. Static parameter. Correlation with operational errors (r = -0.061, N.S.)
2.7	Number of fixes/airports	Number of fixes and controlled airports in each sector. [2]	Capture sector operation. Static parameter Correlation with operational errors (r = 0.219, S.)
2.8	Letters of agreement (LOAs)	Number of letters of agreement for each sector. [2]	Capture sector operation. Static parameter. Correlation with operational errors (r = -0.162, S.)
2.9	Traffic count (TC)	Number of aircraft in the sector within 15-minute time period. [2]	Capture traffic load. Based on ETMS data. Dynamic parameter.
2.10	Traffic level (TL)	Number of aircraft in sector in the previous hour. [2]	Capture traffic load after effects from previous hour. Based on ETMS data. Dynamic parameter.
2.11	Entries	Number of new aircraft in the sector within 15-minute time periods. [2]	Capture traffic load due to new arrivals. Based on ETMS data. Dynamic parameter.
2.12	Average ground	The average ground speed of all aircraft in the sector within	Capture taskload due to Ground speeds.

ID	Variable Name	Description	Purpose
	speed (GS)	15-minute time period. [2]	Based on ETMS data. Dynamic parameter.
2.13	Standard deviation of average ground speed	The standard deviation of ground speed within 15-minute time period. [2]	Capture taskload due to ground speed differential. Based on ETMS data. Dynamic parameter
2.14	Average altitude (ALT)	The average altitude of aircraft in the sector within 15-minute time interval. [2]	Capture taskload due to altitudes used. Based on ETMS data. Dynamic parameter.
2.15	Standard deviation of average altitude	Measurement of the distribution of altitudes of aircraft within the sector in 15-minute intervals. [2]	Capture taskload due to altitude differential. Based on ETMS data. Dynamic parameter.
2.16	Course bins	A count of the number of different increments of 20 degrees in bearing which are occupied by at least one aircraft in the sector for each 15-minute period. This is a measure of the complexity of traffic with regard to course within the sector. [2]	Capture the bearing difference in the sector. Based on ETMS data. Dynamic parameter. (I am not sure what this measure means)
2.17	Transitions	Number of aircraft changing altitude in a 15-minute period. [2]	Capture taskload due to transitions. Based on ETMS data. Dynamic parameter.
	Complexity	*= TC + TC + AVG_GS + STD_GS + STD_ALT + TR + STD_BETA* [2]	Capture complexity at sector level.
3	*Chatterji, G. B., Shridhar, B, 1997, Measures of Airspace Complexity, Preliminary Draft and Unpublished Work, NASA Ames Research Center.*		
3.1	Maximum terrain elevation	Fixed number [3]	Static
3.2	Usual cloud ceiling	Fixed number [3]	Static
3.3	Volume of airspace available	Fixed number [3]	Static
3.4	Number of merging points	Fixed number [3]	Static

ID	Variable Name	Description	Purpose
3.5	Number of neighboring sectors that hand-off traffic	Fixed number [3]	Static
3.6	Number of neighboring sectors that accept traffic hand-offs	Fixed number [3]	Static
3.7	Sector operating procedures	Fixed number [3]	Static
3.8	Navigational aids available	Fixed number [3]	Static
3.9	Surveillance equipment available	Fixed number [3]	Static
3.10	Aircraft mix	See formula [3]	Dynamic
3.11	Traffic density	See formula [3]	Dynamic
3.12	Available airspace	See formula [3]	Dynamic
3.13	Operations near reserved airspace	See formula [3]	Dynamic
3.14	Operations near sector boundaries	See formula [3]	Dynamic
3.15	Flight mode	See formula [3]	Dynamic
3.16	Onboard equipment	See formula [3]	Dynamic
3.17	Horizontal proximity	See formula [3]	Dynamic
3.18	Vertical proximity	See formula [3]	Dynamic
3.19	Time-to-go	See formula [3]	Dynamic
3.20	Groundspeed variability	See formula [3]	Dynamic
3.21	Conflict resolution	See formula [3]	Dynamic
3.22	Preferred path	See formula [3]	Dynamic

ID	Variable Name	Description	Purpose
3.23	Shape of traffic geometry	See formula [3]	Dynamic
4	*Position Classification for Air Traffic Control, Series ATC 2152, 1997, Draft*		
4.1	Sustained traffic index (Dt)	*Dt* = 1 + (*Cav2*/*Cav1*) *Cav1* is the average unweighted hourly count for busiest 1830 hours. [4] *Cav2* is the average unweighted count for the second busiest 1830 hours. [4]	Used for classifying ARTCC or TRACON business/complexity. Post processing is necessary.
4.2	Proposed ATC classification system	Based on weights for each type of operation (e.g., radar, VFR, jet traffic, prop/turbo-prop combination). [4]	Used for classifying ARTCC or TRACON business/complexity. Do not know if this was accepted. Need post processing
5	*McNally, B.D., Laudeman, I.V., Mayhugh, B., 1997, Field Test Evaluation Plan for a Conflict Prediction and Conflict Resolution System, NASA Ames Research Center.* *Shridhar, B., Seth, K. S., Grabbe, S., 1998, Airspace Complexity and its Application in Air Traffic Management, 2nd USA/Europe Air Traffic Management R&D Seminar.*		
5.1	Traffic density (TD)	Number of aircraft in the sector. [5]	Weight = 1.0
5.2	Heading change (HC)	The number of aircraft that made a heading change of greater than 15 degrees during the analysis time interval. [5]	Weight = 2.4
5.3	Speed change (SC)	The number of aircraft that had a computed airspeed change of greater than 10 knots or 0.02 mach during the analysis time interval. [5]	Weight = 2.45
5.4	Altitude change (AC)	The number of aircraft that made an altitude change of greater than 750 feet during the analysis time interval. [5]	Weight = 2.94
5.5	Speed differential (SD)	The number of aircraft that had a speed difference of greater than 150 knots from the average speed in the sector during the analysis time interval. [5]	Weight = 3.72
5.6	Minimum distance 0-5 nm (MD 0-5)	The number of aircraft that had a Euclidean distance of 0-5 nm to the closest other aircraft at the end of the analysis time	Weight = 2.45

ID	Variable Name	Description	Purpose
		interval, excluding the conflicting aircraft. [5]	
5.7	Minimum distance 5-10 nm (MD 5-10)	The number of aircraft that had a Euclidean distance of 5-10 nm to the closest other aircraft at the end of the analysis time interval, excluding the conflicting aircraft. [5]	Weight = 1.83
5.8	Conflict predicted 0-25 nm (CP 0-25)	The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the of the analysis interval is 0-25 miles. [5]	Weight = 4.00
5.9	Conflict predicted 25-50 nm (CP 25-40)	The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the of the analysis interval is 25-40 miles. [5]	Weight = 3.00
5.10	Conflict predicted 40-70 nm (CP 40-70)	The number of aircraft predicted to be in conflict with another aircraft whose lateral distance at the end of the analysis interval is 40-70 miles. [5]	Weight = 2.11
	Complexity =	Weighted sum of all the above variables.	Composite dynamic density metric.
6	*Knecht, W., Smith, K., and Hancock, P.A., 1996, A dynamic conflict probe and index of collision risk, Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting.*		
6.1	Index of collision risk	$Dt = \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{1}{[dij(t)/c]^a}$ N = Number of aircraft dij = distance between two aircraft not separated by altitude c = normalization constant, equal to 5 nm, the minimum allowable lateral separation a = weighting factor set to 3 [6]	Based on separation as the most important factor in collision risk estimation.
7	*Wyndemere, 1996, An Evaluation of Air Traffic Control Complexity, Final Report, Contract Number NAS2-14284 (NASA contract).*		
7.1	Aircraft count (ACT)	Number of aircraft in a sector. [7]	
7.2	Angle of convergence in conflict situation (ANG)	Measurement of the severity of each conflict situation based on the conflict geometry. [7]	Conflicts with small convergence angles are difficult to handle.

ID	Variable Name	Description	Purpose
7.3	Number of aircraft climbing or descending (CoD)	Count of the number of aircraft that are in climb or descent at an instant in time. [7]	
7.4	Closest point of approach (CPA)	Weighting of the number of aircraft that are within a threshold separation of each other at any instant in time. [7]	CPA thresholds are between 8 and 13 miles. One unit for aircraft that are below 8 CPA and 0.5 unit for aircraft that are between 8 and 13 CPA.
7.5	Aircraft density (DNS)	Aircraft count divided by the usable amount of sector airspace. [7]	
7.6	Level of knowledge of intent of aircraft (INT)	Level of information about the intent. Three categories: current operations, half free flight, and full free flight. [7]	Zero complexity for current operations, 0.5 for half free flight, and 1 for full free flight.
7.7	Neighbors (NBR)	Aircraft that are predicted to be within a threshold separation. [7]	One unit for each aircraft that is within 10 lateral miles and 2000 vertical feet.
7.8	Proximity of aircraft to sector boundary (PRX)	Count of the aircraft that are within a threshold distance of a sector boundary. [7]	Greater coordination and monitoring is required when aircraft are closer to the sector boundary.
7.9	Proximity of potential conflicts to sector boundary (PRX-C)	Count of the predicted conflicts that will occur within a threshold distance of a sector boundary. [7]	Controller will have less time to resolve a conflict situation that is near a sector boundary. One unit for each conflict that is within 10 miles of sector boundary and 0.5 unit for each conflict that is within 20 miles of the sector boundary.
7.10	Airspace structure (STR)	Measure of conformance of the traffic flow through a sector to the geometry of the sector. Calculations using major axis, aspect ratio, and difference in heading and the major axis. The squared deviation from the major axis of the sector is weighted by the aspect ratio and then summed over all aircraft. [7]	Complexity may increase if majority of aircraft fly against the grain.

ID	Variable Name	Description	Purpose
7.11	Variance in aircraft speed (VAS)	Measure of the variability of ground speed of all aircraft in the sector. (e.g., standard deviation) [7]	
7.12	Variance in directions of flight (VDF)	Measure of the variability of heading of all aircraft in the sector. [7] $\frac{1}{(n)(n+1)}\sum_i \sum_{j,j\neq i}\left(hdg_i - hdg_j)^2\right)$	A higher heading variability of the traffic situation provides less organization of the traffic flow. Controller can group individual aircraft together with lower heading variability.
7.13	Airspace structure (STR)	Description of sector size and structure. [7]	Capture sector geometry related difficulty (narrow, long, etc.)
7.14	Crossing altitude Profiles (CAP)	Count of number of aircraft pairs in which one aircraft will be climbing and one aircraft will be descending through the same altitude. [7]	
7.15	Altitude variation (VAA)	Measure of the variability of altitude of all the aircraft in the sector. [7]	No evidence from SMEs about its validity.

References

Breitler, A., L, Lesko, M. J., Kirk, K. M., 1996, Effects of Sector Complexity and Controller Experience on Probability of Operational Errors in Air Route Traffic, CAN Corporation, Task 9, FAA Contract DTFA01-95-C-00002. [2]

Chatterji, G. B., Shridhar, B, 1997, Measures of Airspace Complexity, Preliminary Draft and Unpublished Work, NASA Ames Research Center. [3]
EuroControl. [5]

Knecht, W., Smith, K., and Hancock, P.A., 1996, A dynamic conflict probe and index of collision risk, Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting. [6]

Kopardekar, P., and DiMeo, K, 1997, Dynamic Density Variables, PowerPoint Briefing. [1]

Laudeman, I.V., Brasil, C. L., and Branstrom, R. 1996, Air Traffic Control in Restructured Airspace: A Study in Tactical Decision Making, Power point presentation.

McNally, B.D., Laudeman, I.V., Mayhugh, B., 1997, Field Test Evaluation Plan for a Conflict Prediction and Conflict Resolution System, NASA Ames Research Center. [5]

Mogford, R.H, Guttman, J.A., Morrow, S. L., and Kopardekar, P, 1995, The complexity construct in Air Traffic Control: A review and Synthesis of the Literature, DOT/FAA/CT-TN-95/22, FAA Technical Center: Atlantic City.

Position Classification for Air Traffic Control, Series ATC 2152, 1997, Draft. [4]

RTCA Task Force 3 Free Flight Implementation Report, 1995, RTCA: Washington DC.

Shridhar, B., Seth, K. S., Grabbe, S., 1998, Airspace Complexity and its Application in Air Traffic Management, 2nd USA/Europe Air Traffic Management R&D Seminar.

Wyndemere, 1996, An Evaluation of Air Traffic Control Complexity, Final Report, Contract Number NAS2-14284 (NASA contract). [7]