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EXPLORING A NOVEL METRIC OF AIR TRAFFIC CONGESTION

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ABSTRACT

The Federal Aviation Administration's (FAA) current metric of air traffic congestion is a simple count of the number of aircraft in a sector. In previous research (Knecht and Smith, 2001) we showed that, in actual practice, this count seems to be a modest predictor of separation maintenance as measured by operational errors (OE) and the minimum range achieved by the two closest aircraft during a given time period (*Rmin*).

At that time we also presented a novel flightdeck-based congestion metric which we now expand to a ground-based ATC metric of sector-wide congestion. A method is presented to formulate and parameterize this metric using regression analysis of Monte Carlo simulation data. Finally, the performance of this new metric is compared to that of the existing FAA metric on the same data set.

INTRODUCTION

Lately we have been proposing a radical reconceptualization of the four-dimensional constraints on aircraft maneuver (Knecht & Smith, 2001). We call this the *maneuver space* (*MS*) and have demonstrated that a congestion metric based upon it is capable of predicting 50% more of the variance in the minimum separation between aircraft than does the raw count of aircraft alone.

The data for that test were acquired in a series of laboratory experiments using realistic simulations of free flight scenarios and currently certified commercial airline pilots as participants. That kind of data is costly to acquire. Here we use a different kind of simulation to generate large amounts of data quickly and efficiently. The results make predictions that are not only interesting in their own right, but also serve as a heuristic to guide future experimental work.

METHODOLOGY

A useful way to study air traffic congestion is to begin by examining the pure statistical case of random traffic flowing through an arbitrary volume of airspace. This is analogous to unrestricted free flight, and represents the end of the spectrum where there would be no air traffic management (RTCA, 1995). To model this extreme condition, we perform Monte Carlo simulations--large numbers of individual simulations with certain key flight parameters (inputs) selected at random from known statistical distributions at the start of each individual simulation. The resulting distribution of inputs models a broad range of traffic situations in which aircraft would fly at many altitudes, a range of speeds, and in many directions. The purpose of this is to give us an idea of how air traffic would unfold in the absence of human intervention. This baseline can then be used later as a yardstick to compare how well pilots and controllers handle similar situations.

To generate these Monte Carlo simulations we created a computer program named SCAMP, for Sector Congestion Analytical Modeling Program. Written in the scientific visualization language *Mathematica* (Wolfram Research, 1999), SCAMP allows us to specify the physical shape of an air traffic control sector, to generate as many aircraft as desired, to assign headings, speeds, altitudes, and rates of climb to these aircraft, and to assess their behavior as they "fly the sector" as many times as needed to obtain statistically reliable averages. This gives us the ability to vary key parameters such as sector size, minimum and maximum aircraft speeds, the number of aircraft, maximum climb and descent rates, and the percent climbing/descending to see how these factors influence sector congestion.

Figure 1 shows two views of a typical simulation involving 20 aircraft. Figure 1a. shows all aircraft in the simulation while Figure 1b. shows the one conflict pair that just happens to result from this particular combination of input parameters. By studying thousands of such simulations we get a reliable, representative statistical sense of the effect of varying any given parameter.

In this research we were primarily concerned with seeing how varying the number of aircraft would affect traffic conflicts. So we modeled a “generic” rectangular sector 200 x 200 nm wide x 10000 ft in altitude. As few as 4 and as many as 49 aircraft were allowed to assume a) a random (within limits) initial position outside the sector, b) a random heading from 0-360 degrees, and c) a random ground speed between

400-450 kt. Additionally, an average of 15% of the aircraft were allowed to climb or descend, each at a fixed initial rate from between 0-2000 ft/min. All parameter probability density functions except number of aircraft were square functions, meaning that there was an equal probability of assuming any value within the specified range. The number of aircraft was varied along a logarithmic scale, namely the number of aircraft at each block of trials was equal to that of the previous block times 1.3, rounded to the nearest whole number. This produced a total of 11 values for sector aircraft count (4, 5, 6, 8, 10, 13, 17, 22, 29, 38, and 49). The advantage of a logarithmic scale is that it gives fine resolution at small values, where change occurs most rapidly, while still allowing large values to be examined as well. Each value of the number of aircraft was run 100 times, giving a total of 11 blocks of 100, for a total of 1100 simulations.

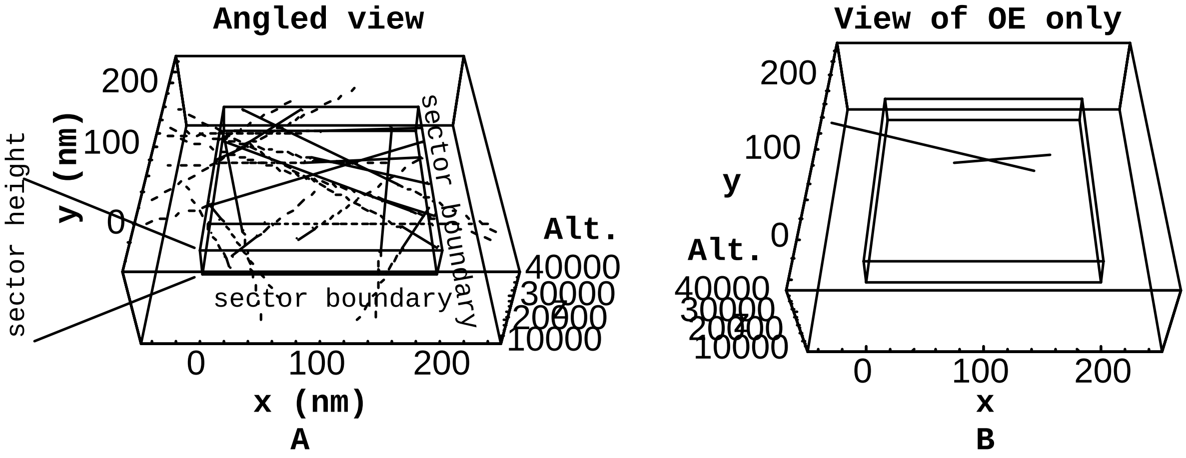

Figure 1. (A) A typical simulation showing an air traffic control sector and the random trajectories of 20 aircraft passing through it. (B) The single traffic conflict pair which resulted by chance from that particular simulation.

Two important considerations need to be noted here. First, these initial parameters were arbitrary values chosen to explore the full extent of one plausible parameter space. Second, we were simply trying to model "average" traffic situations in an "average" sector, in full knowledge that there is truly no such thing. For instance, we are completely aware that commercial aircraft rarely climb at a full 2000 ft/min (although they certainly can descend at that rate). Further, there are no rectangular 200 x 200 nm x 10000 ft control sectors in the US, particularly ones in which 15% of aircraft change altitude at any given time. However, it was not the point to model existing sectors during this initial phase. The idea was simply to develop a program capable of taking a set of specified initial conditions and begin exploring how it performed. And what is typically done in cases like this is to start by modeling a simple, ideal situation and then expand later to more complex and realistic circumstances as experience guides and need dictates.

The key condition we wanted to examine initially with SCAMP centered around the way OEs and traffic congestion vary as the number of aircraft is varied. Operational errors are defined as intrusions by one aircraft into the "protected zone" of another. Our definition of the protected zone followed that provided by the RTCA (1995)--a cylindrical region, five nm in radius by 1000 ft high, with the "protected" aircraft at its center.

During operation, what SCAMP does is to send a "pulse" of aircraft through the sector. This pulse assumes an inverted-V shape across time similar to the one shown in Figure 2.

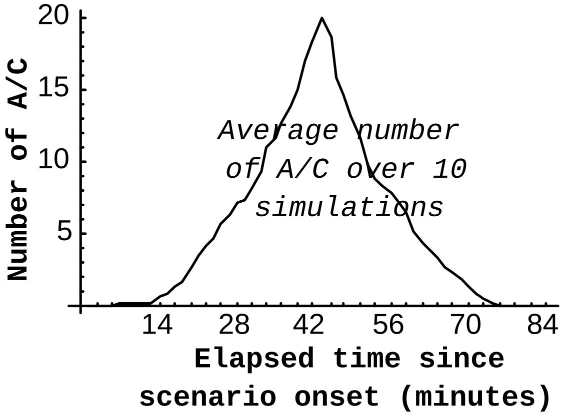

Figure 2. Time plot of the number of aircraft, showing how many aircraft were present inside the sector at any given time, averaged over the course of 10 simulations similar to those in Figure 1. Each simulation involved one such pulse of aircraft moving through the sector over the course of about one simulated hour.

This pulse behavior was designed to allow modeling of the normal ebb and flow of traffic through a sector. Additionally, we knew it would allow future modeling of more complex time-flow patterns. Recall Leibniz's 1673 observation that continuous functions can be well-approximated by series functions (Kreyszig, 1972, p. 384). This implies that even complex time-dependent traffic patterns can be carefully shaped and controlled by combining a series of traffic pulses, each with different numbers of aircraft (equivalent to amplitude) and initiated at different times (equivalent to phase).

SCAMP's pairwise traffic congestion metric was defined by Equation 1. This metric is discussed in greater detail in Knecht & Smith (2001).

$$D_{MS} = \int_{-k_h\sigma_h}^{+k_h\sigma_h} \int_{-k_s\sigma_s}^{+k_s\sigma_s} \int_{-k_a\sigma_a}^{+k_a\sigma_a} \frac{1}{\sigma_{h,s,a}\sqrt{2\pi}} e^{\frac{-(x_{h,s,a})^2}{2\sigma_{h,s,a}^2}} dh\,ds\,da \qquad (1)$$

Each component of Equation 1 is constrained by definition to lie within the range 0-1.0. Accordingly, the multiplicative whole must lie between 0-1.0 also. Values of zero for an aircraft pair represent "no congestion", meaning that no conflict is present--no OE is predicted--and therefore no avoidance maneuver is necessary for that pair. Values of 1.0 represent "complete congestion", meaning "there is absolutely no evasive maneuver possible which would resolve the conflict". Obviously, therefore, values of 1.0 are extremely rare, and typical conflicts generate values in the range of 0.1 to 0.5, depending on the values assigned the standard deviations for heading, speed, and altitude. In the data presented here, the values for σ_h, σ_s, and σ_a were 1 degree, 20 kt, and 500 ft respectively.

The global model used to assess congestion across all aircraft pairs during a traffic simulation was the simplest one possible--for all OEs in an individual simulation the value of the SCAMP metric was simply summed to form a single number. This number combined the effect of both the number of conflicts and the contribution of each to congestion created by the geometry of all relevant aircraft involved.

RESULTS

Figure 3 shows a plot of the number of OEs as a function the number of aircraft in the sector for 1100 simulations. The plot indicates that the number of aircraft in the sector accounts for about 75% of the variance in the OE data. This surprising finding needs to be tempered by two considerations, however. First, experience tells us that the number of aircraft is only a weak practical predictor of subsequent operator performance in resolving actual conflicts (Scallen et al, 1995; Scallen, Smith, & Hancock, 1997; Smith & Hancock, 2000). Second, the sampling variance is still great enough to make accurate prediction of OEs difficult, especially for large numbers of aircraft. For example, given 49 aircraft, our prediction line shows that, on average, we expect seven OEs. But there is roughly a 78% chance that the actual number on any given occasion will lie somewhere between five and nine ((13+16+13+18+18)/100 = .78).

Nonetheless, this uncertainty does not detract from the surprising finding that the number of observed OEs here is far beyond what intuition might lead us to believe. Given as few as six aircraft per hour under these circumstances we predict about a 13% chance of at least one OE occurring. Given 22 aircraft, the odds rise to about 72%. The lesson is clear: Someone has to monitor and maintain separation in free flight because it is guaranteed to be a problem otherwise. Reliance on the "Big Sky Theory" might or might not offer some assurance that true collisions should be rare, but here we have a clear demonstration that OEs should not be rare at all.

Figure 4 shows the comparative performance of the SCAMP metric, given the same task of predicting OEs. Given exactly the same circumstances, SCAMP accounts for approximately 96% of the variance. This illustrates that the SCAMP metric is inherently a better predictor of operational errors than a simple count of the number of aircraft. The reason for this is straightforward: SCAMP is based, not only on the number of aircraft and sector geometry, but also on traffic geometry—all three of the key determinants of average separation in ballistic flight. SCAMP has to be a better predictor because it takes more of the critical information into consideration.

Another interesting result can be seen by examining the frequency distributions shown at each level of OE in Figure 4. What these distributions tell us is that, given any observed non-zero number of OEs, there we can expect some variation in the *seriousness* of those conflicts. In other words, traffic geometry can be expected to render some conflicts harder to resolve than others. Maneuver is more constrained in some situations and that is what makes conflict resolution difficult. And the degree to which that is the case is precisely what SCAMP is measuring.

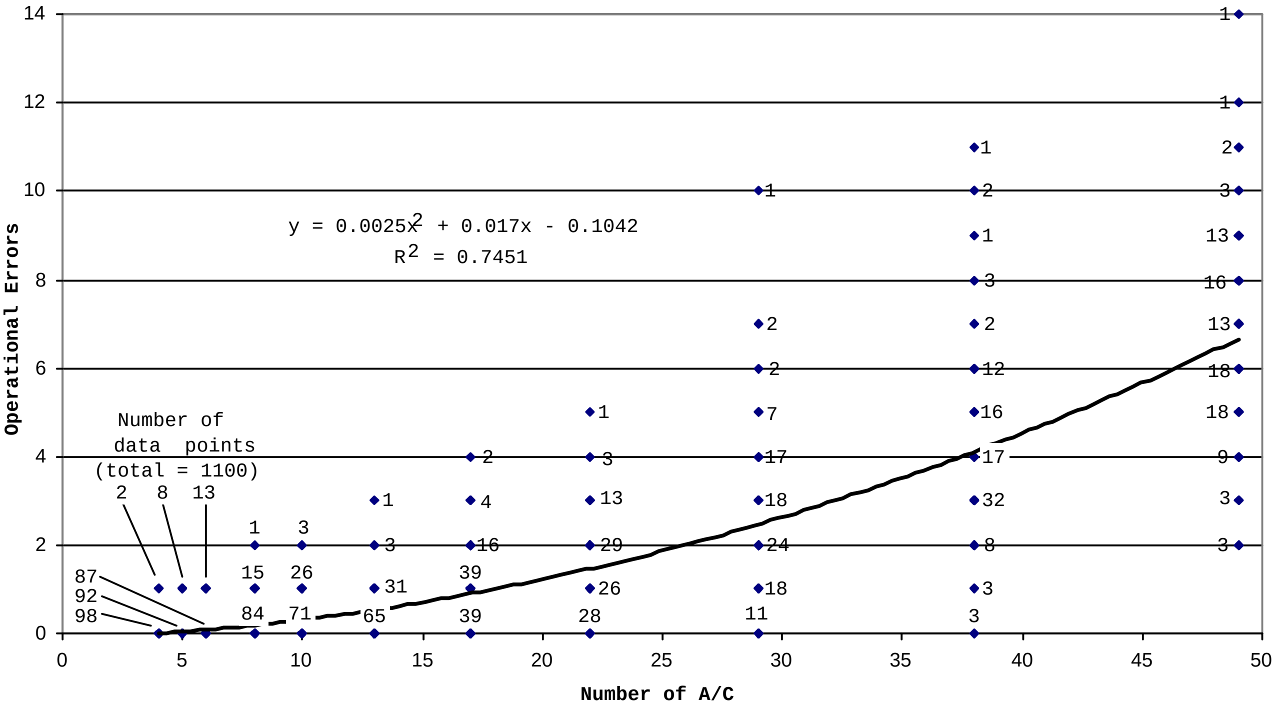

Figure 3. Plot of OEs as a function of the number of aircraft for 1100 simulations. The curved best-fit line shows the number of OEs predicted at each value of aircraft count. Note that number of aircraft accounts for 74.51% of the overall variance in OEs, but that there is still considerable uncertainty about the predicted value.

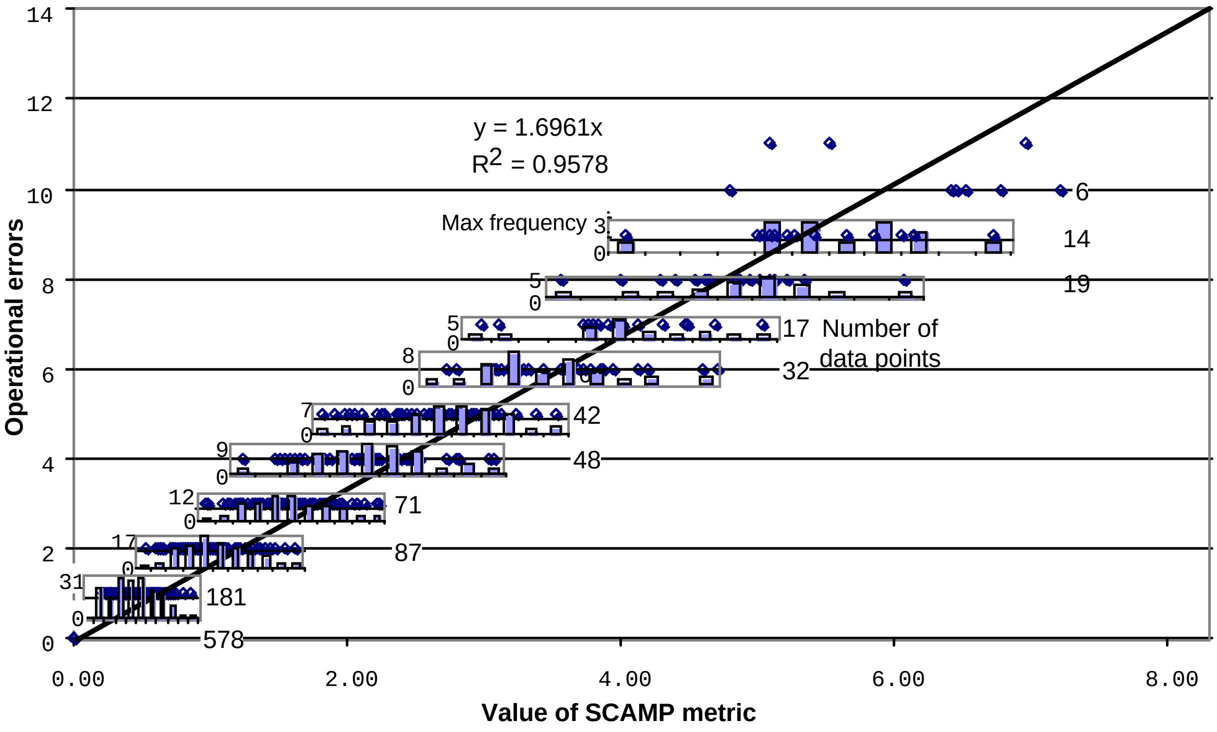

Figure 4. Plot of OEs as a function of the SCAMP metric for the same 1100 simulations. The linear best-fit line shows the number of OEs predicted at each value of the metric. Frequency distributions show how true congestion may vary at each level of OE. SCAMP accounts for 95.78% of the variance in OEs.

DISCUSSION

It is commonly known and accepted by aviation professionals that the number of aircraft in a sector is a modest predictor of how difficult it will be to maintain aircraft separation in that sector (Rodgers, Mogford, & Mogford). Knecht & Smith (2001) examined the strength of this relationship from the pilot's point of view, demonstrating that only 16% of the variance in OEs made by commercial airline pilots in simulated free flight could be explained by the number of aircraft present. This underscored a very real need to factor in traffic geometry as well as density into a predictive metric of airspace congestion.

The true difficulty of finding solutions to traffic conflicts is clearly a function of the degree to which maneuver of the conflicting aircraft is constrained. This observation leads to the conceptualization of a maneuver space associated with each aircraft. The MS conceptually represents the maneuvers an aircraft can physically make. Within the MS can lie conflict regions (CR) representing maneuvers the pilot should avoid, given the goal of maintaining separation with other aircraft.

Together, the MS and CR offer a principled approach to creating a mathematical metric theoretically and empirically capable of out-performing the FAA's current measure of sector congestion. Figures 3 and 4 show that this is the case in theory. Such a metric is theoretically bound to better predict OEs because it takes more of the available situational information into account. In practical terms it ought to also be a better predictor because it is based on maneuver constraint. And maneuver constraint not only captures the fact that a conflict is predicted to occur—it also describes how difficult that conflict will be to resolve.

Two issues remain to be researched. The first involves verifying that an advanced metric such as this actually will work better in practice than what we have already. This is an empirical question and simply has to be tested using air traffic controllers as participants.

The second issue concerns whether or not the additional gain in usefulness of this metric would be worth the cost of incorporating it into current ATC workstations. Our first research estimates perhaps a 50% benefit in terms of actual, real-world conflict resolution. Part of this estimate involves reducing the quantity of OEs while the rest involves increasing the quality of resolutions. It becomes increasingly clear that *detecting* traffic conflicts is technically easier than *resolving* them, particularly when we are trying to do that efficiently. It is here that the MS/CR representation can be expected to excel, not only at predicting the relative difficulty of any given conflict, but also in making plain what the most efficient solution to that conflict will be. Demonstrating this will be the subject of future research.

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