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Maneuver Stereotypes in Airborne Conflict Resolutions

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The roles and responsibilities of air traffic controllers and pilots are shifting in the advent of the NextGen air traffic management infrastructure, which also involves high levels of automation. It is important to understand just how large departures from the current ingrained practices the NextGen procedures represent, particularly in extremely safety-critical tasks such as airborne conflict resolutions. Pilots' conflict resolution maneuver preferences have received some attention, but corresponding research on air traffic controllers' practices is almost nonexistent. We analyzed 87 samples of aircraft track data involving conflict alerts and subsequent resolution maneuvers from Atlanta center. Vertical conflict resolution maneuvers were used in the majority of the cases examined. Within the vertical dimension, reductions of current vertical change (climb or descent) were collectively the most frequent resolution maneuver type, but descents were twice as frequent as climbs. Conflict resolution maneuvers furthermore do not seem to be independent from conflict geometries.

The NextGen air traffic control (ATC) and -management (ATM) technologies and procedures will fundamentally change the roles of pilots and air traffic controllers as well as their tasks and task environments. The putative increases in the system capacity and efficiency will be achieved through extensive use of automation, including automated conflict alerting. Although there is already much experience of such systems in both ATC (Conflict Alert, or CA; Nolan, 1998) and in cockpits (Traffic Alert and Collision Avoidance System, or TCAS; Bliss, 2003; Chappell, 1990), procedures for shared conflict avoidance and resolution are still being designed. As researchers and designers consider the implications of these procedures, it is imperative that they remain harmonious with controllers' current techniques of managing traffic and in particular with ingrained separation maneuvers used in response to potential midair conflicts. It is especially important to avoid generating pilots' rules-of-the-road for self-separation, or automation-based conflict avoidance advisories that are at odds with current ATC conflict avoidance techniques. This paper describes an effort to determine the maneuver stereotypes of en route controllers' responses to conflict alerts in operational conditions.

Pilots' Maneuver Preferences

A fair amount of research has been devoted to examining conflict resolution maneuver stereotypes among pilots (e.g., Alexander, Merwin, & Wickens, 2005: Thomas & Rantanen, 2006; Thomas & Wickens, 2008). This is primarily due to the criticality of collision-avoidance maneuvering in response to airborne collision detection systems (e.g., TCAS and Cockpit Display of Traffic Information, or CDTI), often under severe time constraints (seconds) and without coordination with ATC or other aircraft in the vicinity. Note, however, that TCAS always prescribes a maneuver, and it is assumed that if pilots respond at all, they will always comply in a vertical direction specified by the TCAS algorithm. This in contrast to the CDTI, where maneuver choice is up to the pilot as the direction of conflict resolution is not envisioned to be explicitly commanded by the automation. Research on CDTI generally reveals that pilots tend to prefer vertical maneuvers over lateral ones, reflecting perhaps the greater expediency and reduced complexity of such maneuvering (Thomas & Wickens, 2008). However the data are somewhat ambiguous regarding the extent to which the particular geometry of a conflict dictates the direction of a maneuver. Some faint trends were observed by Thomas and Wickens, revealing that head-on conflicts (versus crossing or overtaking) tended to induce relatively more lateral maneuvering.

Air Traffic Controllers' Maneuver Preferences

Investigation of conflict avoidance maneuver preferences among air traffic controllers is substantially more difficult than research on pilots' preferences. There are several good reasons for the paucity of empirical research on this topic, many of which emphasize the differences between pilots' and controllers' tasks and task environments, even at the dawn of the era of distributed control and shared separation responsibility. The main difference between pilots' and controllers' separation responsibilities under mature free flight or NextGen operations is that pilots are primarily concerned about their own aircraft and their attention extends little beyond those other aircraft that pose an immediate or near-immediate threat of loss of separation. Air traffic controllers must concern themselves with the 'big picture' and traffic flows rather than individual aircraft pairs. Their goal is to create conflict-free traffic flows such that they do not need to devote undue attention to individual conflicts. Also, controllers are always responsible for a much larger number of aircraft that any pilot in any situation, and effective management of their own workload is critical to their performance. However, the CA data examined here clearly represent exceptions to this general *modus operandi* and may reveal different conflict resolution patterns that are closer to pilots' demonstrated preferences.

There are very few laboratory studies on controllers' conflict resolution maneuver preferences, and results from such settings must be evaluated against the particular experimental conditions and airspace designs. Rantanen, Yang, and Yin (2006) examined controllers' separation preferences in a simulator study with a simplified airspace and traffic patterns. Vertical separation (i.e., commanding planes to climb or descend, or remain at an intermediate altitude) was much preferred over vectoring (lateral maneuvers). Controllers have also been shown to prefer the vertical dimension for separation in other contexts (Rantanen & Nunes, 2005). Vertical (altitude) or longitudinal (speed) maneuvers typically preserve traffic flows along regular routes and thus reduce the 'problem space' for the controller along those, simplifying their monitoring task. The maneuver preferences observed by Rantanen et al. (2006) undoubtedly reflect the very constrained and relatively small airspace used in the simulation with little room for vectoring (i.e., lateral maneuvering) and few opportunities for routing changes.

Purpose of the Study

In spite of the importance of this topic for aviation safety, and in particular for understanding how controller's tendencies may either reinforce or contradict pilot tendencies, no data appear to exist regarding the actual controller conflict avoidance behavior with live traffic. The intent of this paper is to bring insight to this process, using the operational ATC en route data from controllers responding to conflict alerts at five Air Route Traffic Control Centers (ARTCCs), with emphasis on one large one (see Wickens et al., 2008 for details). Our focus is on two key aspects of the data: (1) what tendencies to controllers show in terms of instructing lateral versus vertical maneuvers, and, within the latter category, climbs vs. descents, and (2) how are these tendencies mediated or influenced by the particular geometry of a conflict. A third aspect of these data pertaining to how controller's responses are mediated by alert reliability (e.g. false alert rate) is reported in detail by Wickens, Rice, Keller, Hughes and Hutchins (2009) in this volume

Method

This research was done on a subset of data from a greater research effort, involving a large set of conflict cases from five ARTCCs: Houston (ZHU), Indianapolis (ZID), Salt Lake City (ZLC), Los Angeles (ZLA), and Atlanta (ZTL). Much of the results reported in this paper is based only on the data from ZTL, which was the only center thus far receiving a geometry x maneuver contingency analysis. However, overall maneuver data (independent of contingency analysis) was available from all five centers, and are reported below. These data were originally provided to researchers at the Federal Aviation Administration (FAA) Technical Center (Allendoerfer, Friedman-Berg, & Pai, 2007) for analysis, and to us by the FAA in cooperation with National Air Traffic Controllers Association (NATCA). Data for each aircraft pair in conflict consisted of predicted point of closest approach, time of alert, and the radar tracks and altitudes of the aircraft, allowing for analyses of the actual conflicts as they were played out (see Wickens et al., 2008, for details). Alas, these data could not be linked to voice transcripts for additional detail (see Allendoerfer et al., 2007).

Each single conflict was defined as an encounter between two aircraft in a pair, which triggered at least one CA (repeated CA onsets for a given encounter might occur as a given pair went in and out of conflict). For each case, approximately six minutes' worth of actual track data of the two aircraft in conflict were recorded; these track data included the x- and y- (latitude and longitude) and z-(altitude) coordinates sampled every 10 seconds. These coordinates were plotted separately for horizontal and vertical trajectories, from where the conflict geometries and maneuvers performed to resolve the conflict could be determined visually. The geometries were classified into three vertical and three horizontal categories; in addition, five classes of maneuvers were defined.

Vertical geometry. The relative vertical behavior of the two aircraft in a pair prior to the alert was categorized as either converging vertically, where one aircraft was climbing and the other descending, or parallel climbs or descents, or both aircraft level.

Lateral geometry. Aircraft trajectories in the horizontal plane were classified into three categories, either converging, diverging, or parallel. In the case of parallel tracks, one aircraft was often overtaking the other. Parallel approaching tracks (e.g., near opposite headings) were classified as 'converging'. Note that diverging lateral tracks could trigger a CA if these involved more rapid convergence on the vertical axis, such that an LOS on the altitude dimension (< 1000 ft) would occur before separation on the lateral dimension (5 miles) is obtained. Note also that vertical and lateral geometries were both applied to every conflict.

Maneuvers. Maneuver type was subdivided into five classes: descend, reduce descent for an aircraft already in descent (e.g., a level off of a descending aircraft), climb, reduce climb, and turn. Either an increase descent or increase climb was simply categorized as a descent or climb, respectively. In the case of joint maneuvers in both the lateral and vertical axes, the CA was assigned to the category of that maneuver which occurred first (earliest). We also reiterate that inferences of an instructed maneuver were made solely from trajectory changes following the CA, since we had no direct access to corresponding voice transcripts (but see Allendoerfer et al., 2007; Friedman-Berg, Allendoerfer, & Pai, 2008). These data were tabulated and analyzed by χ^2-tests for independence.

Results

The maneuvers controllers instructed in response to the impending conflict or as prompted by the CA, as inferred from the aircraft trajectory plots, are depicted in Table 1. A χ^2 goodness-of-fit test on all maneuvers across the five centers (with a null hypothesis of equal proportions of maneuvers) showed significant differences between the five classes of maneuvers, $\chi^2(4, N = 277) = 60.38$, $p < .001$.

Although turns constitute the most frequent single category (36%), these lateral maneuvers occurred much less frequently than those involving vertical trajectory change. This *vertical maneuver domination* was similar to that observed in the previous report and is also consistent with the integrated findings of studies of aircraft (e.g., pilot initiated) conflict avoidance (Thomas & Wickens, 2008).

Descents were commanded twice as frequently as climbs (7% vs. 14%), but modifications to vertical transitions already in progress were equally divided between reductions of climbs and reductions of descents. Collectively, the latter were the most frequent maneuvers. These trends may reflect controllers' concern of the overall fuel efficiency of flights; descending an aircraft is much more fuel efficient than climbing the aircraft beyond its planned altitude, and reductions to climbs and descents already in progress are minimally disruptive to pilots.

Table 1. *Maneuver frequencies across five ARTCCs from where conflict resolution data were obtained.*

	Maneuver										
Center	Climb		Descend		Reduce Climb		Reduce Desc.		Turn		All
ZID	3	(3.37%)	24	(26.97%)	22	(24.72%)	14	(15.73%)	26	(29.21%)	89
ZHU	1	(3.70%)	2	(7.41%)	8	(29.63%)	3	(11.11%)	13	(48.15%)	27
ZLA	3	(5.88%)	4	(7.84%)	10	(19.61%)	4	(7.84%)	30	(58.82%)	51
ZLC	3	(13.64%)	1	(4.55%)	7	(31.82%)	9	(40.91%)	2	(9.09%)	22
ZTL	11	(12.50%)	9	(10.23%)	10	(11.36%)	30	(34.09%)	28	(31.82%)	88
All	21	(7.58%)	40	(14.44%)	57	(20.58%)	60	(21.66%)	99	(35.74%)	277

Our in-depth analysis of contingency between geometry and maneuver was carried out only on 97 CA cases from ZTL. For nine of these there was no maneuver, suggesting that these were false alarms. This roughly 10% non-response rate parallels that reported in the full data set of 497 CA's; the reasons for this are discussed in the Wickens et al. (2009) paper in this volume. Given that the remaining 89 cases involved CA, we expected that most aircraft trajectories would converge. Indeed, a total of 71 aircraft pairs were on either horizontally or vertically converging trajectories and 54 were converging both horizontally and vertically. Conflict resolution maneuvers were more evenly distributed among the maneuver classes. In the majority of cases, controllers either restricted an aircraft's climb (N = 30) or turned the aircraft (N = 28). These data are consistent with the full analysis of the larger 5-center data set, which revealed that vertical maneuvers dominated turns and within the former, reduced climbs were the most prevalent. In particular maneuvers exploiting gravity (reduced climbs and descents) dominated those opposing gravity (climbs and reduced descents) by a ratio of over 2:1.

Contingency Between Geometry and Maneuver Types.

We have discussed the 'main effects' of maneuver type and geometry above (e.g., analyzing the frequency of these categories, independent of the other). Here we focus our discussion on the interaction, or contingencies between the geometry, as perceived by controllers on their display, and the types of maneuvers that were instructed. We examined these contingencies by χ^2 tests for independence. Two contingency tables were created for vertical and lateral geometries and corresponding maneuvers and their combinations. To create these tables we used the three vertical conflict geometry classes and collapsed maneuver classes also into three: turn, [climb or reduce descent], and [descent or reduce climb], for a 3 x 3 table. The rationale for collapsing within the vertical maneuvers was the commonality of the two that worked against gravity, and the two that worked with gravity, as described above.

The results for the vertical geometries approached significance, $\chi^2(4, N = 87) = 8.67$, $p = .069$. The cause of this non-independence is apparent from the data in Table 2; while climbs and reduced descents made up approximately 22% of all maneuvers, these were particularly unlikely to occur in converging vertical geometries (N = 8; 14% of the time). They were also overall disproportionately rarer than other maneuvers, possibly reflecting their fuel inefficiency and disruptive nature for pilots.

Table 2. *Counts of different maneuvers by vertical conflict geometries (expected values in parentheses).*

	Maneuver						
Vertical Geo.	Climb		Desc.		Turn		Total
Converging	8	(13.333)	28	(26.00)	22	(18.667)	58
Level	4	(2.299)	4	(4.483)	2	(3.218)	10
Parallel	8	(4.368)	7	(8.517)	4	(6.115)	19
Total	20		39		28		87

Similarly, three horizontal geometries (converging, diverging, and parallel) were analyzed against the aforementioned three maneuver categories in another 3 x 3 table (Table 3 below). The results were not significant, $\chi^2(4, N = 86) = 3.72$, $p = .44$, but there appears to be a certain degree of dependence between lateral geometry and maneuver tendencies. Turns were much more frequent in converging than in parallel geometries (35% vs. 20%). In both of these analyses some very small expected values (< 5) are noteworthy.

Table 3. *Maneuver counts by horizontal conflict geometries (expected values in parentheses).*

	Maneuver						
Horizontal Geo.	Climb		Desc.		Turn		Total
Converging	15	(14.419)	25	(28.116)	22	(19.465)	62
Diverging	0	(0.930)	3	(1.814)	1	(1.256)	4
Parallel	5	(4.651)	11	(9.069)	4	(6.279)	20
Total	20		39		27		86

We performed one more analysis on combinations of vertical and horizontal geometries (converging—converging, converging—nonconverging, nonconverging—converging, and nonconverging —nonconverging) against the aforementioned three maneuver categories in a 4 x 3 table (see Table 4 below). The test for non-independence was significant, $\chi^2(6, N = 86) = 13.43$, $p = .036$. Turns, representing only 31% of the maneuvers overall, were disproportionately more frequent on geometries with convergence in both axes (40%). Here, we encountered some very small expected values.

Table 4. *A contingency table for combinations of vertical and horizontal conflict geometries and corresponding resolution maneuvers (expected values in parentheses).*

	Maneuver						
Vertical, Horizontal Geometry	Climb		Desc.		Turn		Total
Converging—Converging	7	(10.93)	21	(21.31)	19	(14.76)	47
Converging—Nonconverging	1	(2.33)	7	(4.53)	2	(3.14)	10
Nonconverging—Converging	8	(3.49)	4	(6.80)	3	(4.71)	15
Nonconverging—Nonconverging	4	(3.26)	7	(6.35)	3	(4.40)	14
Total	20		39		27		86

Discussion

In ATC workload management is one of the most critical skills for a successful controller. Consequently, controllers' techniques exhibit certain economy. For example, maintenance of traffic flows is less mentally taxing than keeping track of individual aircraft, and vertical maneuvering is less disruptive to traffic flows than lateral maneuvering. Hence, our results are not entirely surprising: vertical conflict resolution maneuvers (climb, descend, restrict climb or descent) were used in the majority of the cases we have examined. Such maneuvers are often the best solutions to conflicts, especially if the aircraft involved are already in vertical transition. Indeed, reductions of current vertical change (climb or descent) were collectively the most frequent resolution maneuver type. On the other hand, climbs and restricted climbs were the least frequent maneuvers overall in all of our analyses, reflecting the disruptive nature and fuel inefficiency of such maneuvers working against gravity. In the few conflict geometries where they were used in the majority of cases, the difference to other maneuver types was very small. Within the vertical dimension, descents that exploit gravity were twice as frequent as the climbs that oppose it.

We also discovered some indications that conflict resolution maneuvers are not independent from conflict geometries preceding them. Climbs or restricted descents were disproportionately rare in vertically converging geometries, while turns, despite their overall small proportion were frequently employed in resolution of conflicts with converging geometries. We expect these trends to become more salient when the full data set from all five ARTCCs is analyzed, and in much greater detail than was possible here.

It should be kept in mind that 86 cases is not a very large data set when it is divided into 9 or 12 cells in contingency tables. However, the trends apparent in the raw numbers are quite clear and robust. The results reported here are only the first fruits of a continuing research effort, however. We are performing similar analyses on the data from all five centers, and expect to gain a much more detailed insights into controllers' maneuver choices as well as statistically more significant results than here, with only about 20% of the data analyzed. Categorical analysis is common and undeniably valuable way to examine safety data, but its limitations must be acknowledged. Conflict geometries exhibit enormous variability and any classification system necessarily includes very different situations warranting different maneuver choices into the same categories. While this will be less of a problem with the full, 5-center data set, we are also going to treat geometries as a continuous variable allowing more fine-grained measurement of their characteristics.

Finally, we would like to make a case for detailed analysis of operational data, which can reveal patterns and behaviors that could never emerge in simulated laboratory experiments. Routine access to data such as reported here is crucial for the research community to keep up with and contribute to the development of the NextGen systems.

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