DOT/FAA/AM-93/22

Office of Aviation Medicine
Washington, D.C. 20591

AD-A275 986

An Examination of the Operational Error Database for Air Route Traffic Control Centers

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December 1993

Final Report

This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161.

U.S. Department
of Transportation

Federal Aviation Administration

NOTICE

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/AM-93/22		

4. Title and Subtitle	5. Report Date
AN ANALYSIS OF THE OPERATIONAL ERROR DATABASE FOR AIR ROUTE TRAFFIC CONTROL CENTERS	December 1993
7. Author(s) Mark D. Rodgers, Ph.D., Editor	8. Performing Organization Report No.
9. Performing Organization Name and Address FAA Civil Aeromedical Institute P.O. Box 25082 Oklahoma City, OK 73125	10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency name and Address Office of Aviation Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, D.C. 20591	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplemental Notes

This work was performed under task A-C-92-HRR-115.

16. Abstract

Monitoring the frequency and determining the causes of operational errors - defined as the loss of prescribed separation between aircraft - is one approach to assessing the operational safety of the air traffic control system. The Federal Aviation Administration (FAA) refers to the loss of separation standards between aircraft as an operational error (OE). The extent to which separation is lost determines the severity of the error.

The first study examined the relationships between error occurrence, controller workload (number of aircraft and traffic complexity) and causal factors involved. The FAA's Final Operational Error/Deviation Reports for ARTCC facilities during calendar years 1985-88 comprised the data base. A majority of the errors occurred under conditions of below average (25%) or average (39%) complexity. Complexity and number of aircraft were highly correlated. However, there was a significant difference across facilities in average workload during an event. Improved guidelines for quality assurance personnel are needed to insure a more standardized determination and reporting of workload dimensions. Results suggested that the frequency of some of the causal factors varied in response to changes in number of aircraft worked and traffic complexity.

The second study analyzed the workload and causal factors related to the severity of OEs at ARTCCs during 1988-91. Neither the number of aircraft being worked nor air traffic complexity were significantly associated with severity. In general, the causal factors that resulted in greater severity likely involved reduced situation awareness by the controller. The relationship of aircraft profiles and flight levels with OE severity were examined. Facility level differences were reviewed regarding controller workload and awareness of the developing error. More in depth information is needed to determine precisely the manner in which alterations in workload influence the nature of the error process. Both studies point to the need for increasing the level of objectivity in the operational error investigation process.

17. Key Words	18. Distribution Statement
Air Traffic Control, Operational Errors, Human Performance, Human Factors, Workload	Document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGMENT

The authors gratefully acknowledge the assistance of
Gena K. Drechsler
for her effort in the preparation of this manuscript.

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AN EXAMINATION OF THE WORKLOAD CONDITIONS ASSOCIATED WITH OPERATIONAL ERRORS/DEVIATIONS AT AIR ROUTE TRAFFIC CONTROL CENTERS

David J. Schroeder and Lendell G. Nye

INTRODUCTION

In addition to the analysis of aircraft accidents, several other aspects of aviation activity are monitored and evaluated by the Federal Aviation Administration (FAA) to assess the overall safety of the National Airspace System (NAS). This study involves the analysis of data for one such measure, Operational Errors/Deviations (OEDs). An operational error (OE) takes place when an air traffic controller allows less than applicable minimum separation criteria between aircraft (or an aircraft and an obstruction). Standards for separation minima are described in the Air Traffic Control (ATC) Handbook (7110.65, and supplemental instructions). In the context of the Operational Error/Deviation (OED) reporting system, an operational deviation occurs when the appropriate separation standards are maintained, but an aircraft enters airspace assigned to another controller's position of operation or air traffic control facility without prior approval.

Since 1985, the FAA has operated the OED reporting system to track the operational errors/deviations reported across the nation's ATC system. An automatic OE detection system was implemented in domestic Air Route Traffic Control Centers (ARTCCs) in 1984. Under this system, an automatic alarm is triggered whenever minimum separation standards are violated by radar-tracked aircraft. When an OED occurs, the associated facility is responsible for gathering data and completing a report, in accordance with FAA Order 7210.3 (Facility Operation and Administration). Details concerning the air traffic control situation and the involved controller(s) are gathered and summarized on the reporting form. Data gathered via this reporting program are then coded and entered into the OED computerized data base, under the purview of the Office of Aviation Safety. The current OEDS data base contains data from the time of its implementation in 1985. This data base contains OED data from Terminal facilities (radar approach control and towers) and ARTCCs.

This study will focus on data gathered from ARTCCs, also called En Route facilities; Air Traffic Control Specialists (ATCSs) at those facilities primarily handle aircraft traveling between the terminal facilities across the nation. The study was designed to examine relationships between workload (number of aircraft and complexity of air traffic) and causal factors associated with ARTCC OEDs. First, this study examined the relationship between the two workload measures for all ARTCCs combined and determined whether there were significant differences between facilities in either the average number of aircraft being worked or the complexity level reported at the time of the OED occurrence. Using previous OED reporting systems, the results of analyses of 1965 and 1966 data (Kershner, 1968), data from Kinney, Spahn and Amato (1977), and subsequent operational error data Schroeder (1982), indicated a general trend for an increased percentage of errors under "Light" and "Moderate," as compared to "Heavy" workloads. Stager and Hameluck (1990) called for an examination of the causes of operational errors in terms of the conditions existent for the air traffic controller during the operative time-frame of the incident. These conditions included "fatigue, distraction, attitudes, excessive workload, and procedural knowledge." Second, this study determined if certain categories of operational errors occur more or less frequently under the different workload conditions. Sperandio (1971) found that air traffic controllers tended to adopt different methods of operation in response to alterations in workload. Third, the number of OEDs at a given ARTCC has been found (Splawn, Edwards, & Chin, 1988) to be a function of a) primarily, the total number of operations and b) secondarily, the percentage of ATCSs at the facility who have reached full performance level (FPL). This finding for calendar year 1987 was evaluated for consistency over the entire 1985-88 time period and was expanded to include the facility's average complexity of air traffic reported during the OED occurrence as an additional potential predictor of the number of OEDs for the ARTCC facilities.

METHOD

OEDS Data Base

Information was extracted from the data base for all 1985-88 ARTCC OEDs. The "number of aircraft" variable refers to the number of aircraft that were being worked (radar identified and/or established radio communication) at the time of the OED occurrence. Traffic complexity involves the use, by the quality assurance specialist, of a five-point rating scale (traffic was 1- "easy" to 5- "complex") to indicate the "overall difficulty of the controller's task considering weather, traffic mix, variety of operations, limited use of altitudes, airspace available for radar vectoring, coordination requirements, etc." (FAA Form 7210-3). It should be noted that the instructional guide for the form differed from the OED report form in referring to the initial end point as "not complex" and the final as "extremely complex." Workload information was provided by the facility in the final reports. However, final reports were not required for all OEDs that were classified as "minor." Thus, only the final reports with complete controller workload information were included in this study.

The OED data base lists the types of "causal factors" involved in each incident. The causal factors for ARTCCs were categorized as: a) radar display factor - inappropriate use of displayed data, misidentification, etc.; b) communication factor - improper phraseology, readback, etc.; c) coordination factor - between sectors, facilities, etc.; d) data posting - computer entry and processing flight progress strips; and e) position relief briefings - deficiencies in giving or utilizing briefings. An error could involve more than one employee and have multiple contributing causes; therefore, for this study, an error was considered to have involved a given factor if it was identified as a contributing factor for one or more employees. Appendix A provides the definitions of the causal factors from the Final Operational Error/Deviation Report (FAA Form 7210-3).

Analyses

Means and standard deviations were determined for the two workload measures for each year. For comparisons across facilities, the "number of aircraft" measure was separated into three categories; 1-6 aircraft, 7-11 aircraft, and 12+ aircraft. Percentages of OEDs that occurred under three levels of complexity and "number of aircraft worked" conditions were determined for each ARTCC. Causal factors were coded as "0" if the factor was not involved in the error and "1" if the factor was listed as having been involved one or more times in the report. Analyses were confined to those OED records with at least one ATCS employee causal factor and non missing data for (a) the number of aircraft being worked and (b) traffic complexity. Correlation coefficients were computed between the workload measures and error factors. Multiple regression analyses were performed to determine the relationships of several average facility-level conditions with the number of OEDs for the ARTCCs.

RESULTS

The average number of aircraft worked during an OED declined slightly from 1985 to 1988: M=9.6, SD=4.7 (1985); M=9.2, SD=4.5 (1986); M=8.6, SD=4.1 (1987); and M=8.7, SD=4.2 (1988). This was true despite the general increase in the overall number of aircraft operations handled by the ARTCCs, from approximately 32.27 million in 1985 to 35.91 million in 1988. Percentages of OEDs occurring under the five complexity levels for each year are presented in Table 1.

While the percentages of occurrences for the different complexity levels were similar for 1985 and 1986, in the latter two years, there was a slight increase in the percentage of errors that occurred under "easy" conditions (9.8% in 1987 and 10.7% in 1988 versus 4.8% and 4.6% in 1985 and 1986, respectively). Also, across the four years, from 21% to 29% occurred under less

Table 1
Percentages of OEDs Occurring Under each of Five Complexity Conditions, by Year

YEAR	EASY		AVERAGE		COMPLEX
1985	4.8	18.3	39.7	28.6	8.6
1986	4.6	16.7	40.1	29.9	8.6
1987	9.8	15.6	37.8	28.2	8.5
1988	10.7	18.6	38.0	27.3	5.5
Overall	7.4	17.3	38.9	28.5	7.9

Note: $X^2(12)=30.83$; $p<.01$

Table 2
Number of Aircraft Worked During OEDs for Traffic Complexity Categories

TRAFFIC COMPLEXITY	*N* OF OEDS	MEAN # AIRCRAFT	*SD*	MINIMUM	MAXIMUM
Easy	155	4.01	2.0	1	13
Below Average	356	6.03	2.3	1	17
Average	800	8.66	3.2	1	25
Above Average	576	11.41	4.1	3	35
Complex	161	14.30	5.6	5	40
Totals	2048	9.07	4.5	1	40

than average complexity conditions. Furthermore, nearly two-thirds of the errors occurred under average or lower complexity. The interrelationship between the two measures is demonstrated in Table 2. Even though there is a gradual increase in the average number of aircraft worked under the five complexity levels, from 4.01 under "easy" conditions to 14.30 under "complex" conditions, the range within each of the categories is considerable. "Easy" conditions involved from 1 to 13 aircraft and "complex" conditions involved from 5 to 40 aircraft. (Note: involvement of a single aircraft occurred in only 11 of the incidents, a majority of which were operational deviations). Differences across the five categories and the general overlap would seem to raise some questions concerning the criteria used to determine air traffic complexity and whether those criteria are consistently applied across facilities. Under what circumstances would a situation involving 3 aircraft be of "above average" complexity for a particular sector? Likewise, how can a situation involving 25 aircraft be considered to be of only "average" complexity? Additional information and analyses are required to determine the factors most closely related to application of the complexity ratings and whether those ratings should be modified.

Percentages of OEDs occurring under "less than average" ("easy" and "below average complexity"), "average," and "above average" complexity ("above average" and "complex") for each of 22 ARTCCs are presented in Table 3. The Honolulu (ZHN) ARTCC

Table 3
Percentage of OEDs Occurring Under Three Complexity Conditions for each ARTCC

ARTCC	Less Than Average	Average Complexity	Above Average	N
	COMPLEXITY RATING			
ZAB - Albuquerque	27.3%	40.9%	31.8%	44
ZAN - Anchorage	15.4%	34.6%	50.0%	26
ZAU - Chicago	29.1%	45.6%	25.3%	158
ZBW - Boston	18.5%	53.3%	28.1%	135
ZDC - Washington DC	21.1%	29.7%	49.2%	185
ZDV - Denver	17.9%	29.5%	52.6%	78
ZFW - Fort Worth	16.9%	39.8%	43.4%	83
ZHU - Houston	28.2%	37.6%	34.1%	85
ZID - Indianapolis	20.0%	49.0%	31.0%	155
ZJX - Jacksonville	26.4%	44.8%	28.7%	87
ZKC - Kansas City	27.8%	30.6%	41.7%	108
ZLA - Los Angeles	29.4%	24.6%	46.0%	126
ZLC - Salt Lake City	27.0%	35.1%	37.8%	37
ZMA - Miami	23.8%	54.8%	21.4%	42
ZME - Memphis	22.4%	44.7%	32.9%	76
ZMP - Minneapolis	26.8%	49.3%	23.9%	71
ZNY - New York City	27.9%	36.6%	35.5%	172
ZOA - Oakland	25.4%	40.8%	33.8%	71
ZOB - Cleveland	31.1%	32.0%	36.9%	122
ZSE - Seattle	29.0%	29.0%	41.9%	31
ZSU - San Juan	36.4%	21.2%	42.4%	33
ZTL - Atlanta	25.4%	46.5%	28.1%	114
Combined	25.0%	39.1%	35.9%	2039

Note: $X^2(42)=98.42$; $p<.001$

was not included, due to the small number of OEDs (less than 10) in the database. There were marked differences across facilities in the percentages of OEDs occurring under the three complexity levels. While 25% of the OEDs occurred under "less than average" complexity categories, the percentages across facilities ranged from 15.4% at the Anchorage ARTCC to 31.1% at Cleveland and 36.4% at San Juan. Similar differences were noted for "average" complexity (ranging from 21.2% at San Juan to 54.8% at Miami). Percentages of OEDs under "above average" complexity ranged from 21.4% at Miami to 52.6% at Denver. Of the 22 facilities, four (ZAN, ZDC, ZDV, and ZLA) had more than 45% of their OEDs occur under "above average" complexity conditions. In contrast, three (ZAU, ZMA, and ZMP) had 26% or less of their OEDs occur under "above average" complexity conditions. The extent to which these differences reflect actual differences in complexity of the sectors at the various ARTCCs, or to differences in how the complexity ratings are assigned, is not determinable from the available data. Certainly within each facility, it is reasonable to expect that some sectors present more complex and challenging air traffic control situations than others. Also, a sector considered "complex" at one facility might be rated as "average" at another ARTCC. Thus, without additional information concerning the percentage of time ATCSs at the various facilities

Table 4
Percentage of OEDs Occurring Under each of Three Workload Categories for each ARTCC

ARTCC	1-6 AIRCRAFT	7-11 AIRCRAFT	12 OR MORE AIRCRAFT	*N*
	NUMBER OF AIRCRAFT			
ZAB - Albuquerque	22.7%	50.0%	27.3%	44
ZAN - Anchorage	23.1%	11.5%	65.4%	26
ZAU - Chicago	31.0%	43.7%	25.3%	158
ZBW - Boston	45.2%	43.7%	11.1%	135
ZDC - Washington DC	25.9%	49.7%	24.3%	185
ZDV - Denver	15.4%	44.9%	39.7%	78
ZFW - Fort Worth	33.7%	51.8%	14.5%	83
ZHU - Houston	38.8%	43.5%	17.6%	85
ZID - Indianapolis	29.7%	58.1%	12.3%	155
ZJX - Jacksonville	21.8%	43.7%	34.5%	87
ZKC - Kansas City	30.6%	55.6%	13.9%	108
ZLA - Los Angeles	53.2%	39.7%	7.1%	126
ZLC - Salt Lake City	13.5%	32.4%	54.1%	37
ZMA - Miami	16.7%	66.7%	16.7%	42
ZME - Memphis	19.7%	55.3%	25.0%	76
ZMP - Minneapolis	22.5%	49.3%	28.2%	71
ZNY - New York City	39.0%	32.6%	28.5%	172
ZOA - Oakland	29.6%	36.6%	33.8%	71
ZOB - Cleveland	30.3%	41.0%	28.7%	122
ZSE - Seattle	41.9%	32.3%	25.8%	31
ZSU - San Juan	15.2%	36.4%	48.5%	33
ZTL - Atlanta	32.5%	39.5%	28.1%	114
Combined	31.1%	44.8%	24.0%	2039

Note: $X^2(42)=199.45$; $p<.001$

spend controlling traffic under the various complexity or workload conditions it is difficult to determine the primary factors associated with these outcomes.

Differences in percentages of OEDs occurring under different reported workload conditions were also evident in the three categories of "number of aircraft worked" (Table 4). Six facilities (ZAN, ZDV, ZJX, ZLC, ZOA, and ZSU) had more than 30% of their OEDs occur when "12 or more" aircraft were being worked. ZBW, ZFW, ZID, ZKC and ZLA had less than 15% of their OEDs occur under this higher workload condition. Three ARTCCs (ZBW, ZLA, and ZSE) had more than 40% of their OEDs occur under the lower traffic condition (6 aircraft or less). Once again, additional information is needed to clearly understand the basis for these differences. To what extent are the differences related to how determinations are made concerning the number of aircraft handled or to aspects of the underlying traffic conditions?

Correlations between the two workload measures "number of aircraft" (#WRKD) and complexity (CMPLXTY) and the five causal factor categories are presented in Table 5. Z#WRKD refers to the value of the "number of aircraft" measure, following transformation into a *z* score, standardized within each facil-

Table 5
Intercorrelations Between Workload Measures and Causal Factors

	Z#WRKD	#WRKD	CMPLXTY	DATAP	RADARD	COMM	COORD
Z#WRKD	—						
#WRKD	.92**	—					
CMPLXTY	.65**	.61**	—				
DATAP	.11**	.16**	.06*	—			
RADARD	.02	-.01	.06*	-.13**	—		
COMM	-.01	-.01	-.01	-.10**	-.40**	—	
COORD	-.05	-.04	-.05*	.16**	-.23**	-.15**	—
RBRIEF	.05	.09**	.03	.15**	-.06*	-.06*	.08**

Note:
n = 2042, 2-tailed significarce levels
* = $p<.01$
** = $p<.001$
Z#WRKD = number of aircraft being worked-standardized within each facility
#WRKD = actual number of aircraft being worked
CMPLXTY = air traffic complexity rating
DATAP = data posting was a causal factor
RADARD = radar display
COMM = communication
COORD = coordination
RBRIEF = relief briefing

ity, rather than on all facilities combined. The five causal factors were: data posting (DATAP); radar display (RADARD); communications (COMM); coordination (COORD); and relief briefing (RBRIEF). As already indicated, complexity and "number of aircraft" are highly correlated (r=.61). "Number of aircraft" is most closely related to the data posting causal factor (r=.16, p<.001). A statistically significant positive correlation was also noted between "number of aircraft" and the relief briefing factor (r=.09, p<.001). Thus, OEDs involving a greater number of aircraft were somewhat more likely to involve a problem associated with data posting. They were also slightly more likely to involve problems associated with the relief briefing. Complexity also appears to have very small statistical relationships with data posting (r=.06, p<.01) and use of the radar display (r=.06, p<.01). A small but statistically significant negative correlation was noted between complexity and the coordination factor (r=-.05, p<.01). Thus, an error involving coordination was somewhat more likely to occur under lower, rather than higher, complexity conditions. While statistically significant, the practical significance of these results is limited, due to the low magnitude of the correlation coefficients. Significant patterns of intercorrelations were found among types of causal factors within the OED incidents. In particular, when the radar display was involved, communication and coordination factors tended not to be involved (r=-.40, p<.001 and r=-.23, p<.001 respectively).

To provide a better understanding of the relationship between the "number of aircraft" workload measure and the various causal factors, the workload measure for "number of aircraft" was categorized on the basis of the four z score ranges: low through -1.0; -.99 through .99; 1.0 through 1.99; and 2.0 and

Table 6
Causal Factor Types and Number of Aircraft Worked - Categories Standardized Within ARTCC Facilities

CAUSAL FACTOR # OF AIRCRAFT (Z VALUES)	DATA POSTING	RELIEF BRIEFING	RADAR DISPLAY	COMMUNI-CATION	COORDIN-ATION	# OF OEDS IN WORKLOAD LEVEL
≤ -1.0	15.9% n=46	2.4% n=7	49.3% n=143	31.0% n=90	42.1% n=122	290
-.99 - +.99	18.6% n=268	4.0% n=57	58.3% n=839	29.7% n=427	27.5% n=395	1438
1.0 - 1.99	30.3% n=70	6.1% n=14	56.7% n=131	28.6% n=66	25.1% n=58	231
2.0 and >	37.1% n=33	10.1% n=9	56.2% n=50	29.2% n=26	37.1% n=33	89
Overall	20.4% n=417	4.2% n=87	56.8% n=1163	29.7% n=609	29.6% n=608	2048
Chi-square	35.7	12.1	8.0	0.4	29.3	
(df=3)	p<.001	p<.01	p<.05		p<.001	

Note: Results of ***separate*** chi-square tests of OEDs that involved a given causal factor versus those that did not involve that factor (i.e. all others). Row percentage totals exceed 100% because an OED can involve multiple causal factors. n=number of OEDs that occurred under each combination of workload level and causal factor type. %=percentage of OEDs within a workload level involving that causal factor.

greater. Even though the relationships between workload measures and the causal factors were low, the results were consistent with expectations. The percentages shown in Table 6 represent, within a given workload condition, the number of OEDs in which a causal factor was involved, divided by the total number of OEDs for that workload condition. It was possible for multiple causal factors to be listed for a single OED and thus the number of causal factors exceed the number of OEDs. Overall, 20.4% of the OEDs involved data posting. When a relatively large number of aircraft were being handled (z score of 2.0 or more), a data posting causal factor was reported in 37.1% of those OEDs, compared to 15.9% of the OEDs in the lowest workload condition. The Relief Briefing factor was also more likely to be involved at the higher workload conditions. The Radar Display factor was marginally less likely to occur in the lowest workload conditions, and was involved in from 49% to 58% of the OEDs. Coordination tended to be involved more frequently at both low and high workload conditions, compared to moderate or average conditions. Thus, while causal factors were not highly influenced by either of the two workload conditions ("complexity" and "number of aircraft"), there was some evidence that higher percentages of certain error factors occurred at the extremes of the workload distribution, rather than at average to moderate workload conditions.

Table 7 contains results of a regression analysis in which the criterion - average number of OEDs for ARTCC facilities from 1985-88 (EALL) - was evalu-

TABLE 7
MULTIPLE REGRESSION FOR OPERATIONAL ERRORS/DEVIATIONS AT ARTCCS FROM 1985-88

VARIABLE	MEAN	SD	VARIABLE LABEL
EALL	69.8	94.9	Avg. Annual ARTCC Errors
OPSAVG	1,632,680.29	442,995.13	Avg. Facility Operations
FPLRATIO	.66	.11	Ratio FPL to Total ATCSs
CMPLXAVG	3.12	.16	Avg Complexity Reported at Occurrence of OEDs

Dependent Variable = EALL - Avg. Annual ARTCC Errors
Multiple *R* .914
R Square .836 $F_{3,17}$=28.92; p<.001
Adjusted R Square .807

VARIABLE	BETA WEIGHT	PARTIAL CORR.	*F*
OPSAVG	.949	.909	81.41
FPLRATIO	-.332	-.627	11.00
CMPLXAVG	.301	.571	8.22

ated as a function of a) average annual facility operations (OPSAVG), b) the facility's ratio of full performance level (FPL) controllers to total ATCS workforce (FPLRATIO), and c) the facility's average traffic complexity reported at the time of the occurrence of the OEDs (CMPLXAVG). The data for the ratio of FPL/total ATCSs were obtained from the 1987 calendar year report by Splawn, Edwards, & Chin (1988), which approximates the mid-point of the time-frame of the current study.

The set of predictor variables accounted for approximately 84% of the variance in number of ARTCC OEDs, with each measure contributing significantly to the regression equation. The standardized beta coefficients and partial correlations were greatest for the quantitative measure of facility workload (B=.95, r=.91) and similar in magnitude for the FPL experience level (B=-.33, r=-.63) compared with average traffic complexity (B=.30, r=.57). As was found for 1987, the average number of OEDs during 1985-88 tended to be strongly and positively related to total operations and inversely related to the ratio of FPL air traffic controllers. The measure of the qualitative nature of a facility's workload at the time of the OEDs was shown to be a significant additional component in explaining facility differences in the number of OEDs. This last finding was the result of the inverse relationship (r=-.34) between an ARTCC's average operations and average complexity (i.e., ARTCCs with a greater number of annual ATC operations tended to report that their OEDs occurred under less complex traffic conditions). The determination of whether or not comparable facility differences exist in air traffic complexity during non-error conditions requires further evaluation.

DISCUSSION

This study found that both the average number of aircraft being worked and the level of the air traffic complexity during OEDs declined slightly during 1985-88. As expected, there was a strong relationship between the two workload measures reported in the OED database. Differences in the average workload conditions during the OEDs were found across the ARTCCs. Some degree of variability would be expected, given that the workload measures are reported by many different investigators. Although the report form and associated information provides detailed information concerning the evaluation process, certain determinations remain subjective. In particular, the criteria for categorizing air traffic complexity seems to require additional study. It is possible that an analysis of comments provided in the section of the report devoted to "explanation of traffic complexity" could provide some insight into differences in the rating procedures. Also, to what extent and how consistently are the "number of aircraft being worked at the time of occurrence" reported as the number handled at the time of actual loss of separation or as the number handled during a specified time period surrounding the OED?

Some causal factors were found to occur more often under certain workload levels. The strongest association between workload and the type of causal factor contributing to the OEDs was for data posting - which involves computer entry and processing of flight progress strips. However, these relationships were small and tended to be evident only at the extremes of the workload conditions. These findings offer some support to Sperandio (1971), who found that alterations in workload led ATCSs to adopt different modes of operation. Also, the results are consistent with recent research regarding how air traffic controllers handle board management under varying traffic scenarios (Vortac, O.U., et al). A question for future study is whether, and to what extent, air traffic controllers implement less effective a) procedures in response to changes in workload, and b) strategies as a consequence of high workload?

The number of incidents at ARTCCs during the calendar years 1985-88 was found to be positively associated with total number of facility operations, but inversely related to the ARTCC's proportion of air traffic controllers who were at full performance level. This relationship is consistent with previous research on operational errors at ARTCCs for 1987 (Splawn, Edwards, & Chin, 1988). In the current study, it was found that after accounting for the total number of operations and FPL ratio variables, a facility's average air traffic complexity level (reported at the time of its OEDs) was also a significant predictor of total OEDs, with 84% of the variance associated with the OED data subsumed by those three variables. Thus, although most OEDs occurred under average or lower air traffic complexity, this more qualitative measure of workload helped explain the variation in the number of OEDs at en route facilities.

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FACTORS ASSOCIATED WITH THE SEVERITY OF OPERATIONAL ERRORS AT AIR ROUTE TRAFFIC CONTROL CENTERS

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INTRODUCTION

In the history of the Federal Aviation Administration, no aircraft have collided while under positive control in en route airspace. However, aircraft have violated prescribed separation minima and approached in close proximity. This event can occur as a result of either a pilot deviation, or an operational error (OE). In this study, analyses were conducted of data gathered concerning OEs. An operational error takes place when an air traffic controller allows less than applicable minimum separation criteria between aircraft (or an aircraft and an obstruction). Standards for separation minima are described in the Air Traffic Control (ATC) Handbook (7110.65F, and supplemental instructions). While there is considerable complexity in those standards, at flight levels between 29,000 and 45,000 feet, Air Traffic Control Specialists (ATCSs) at en route facilities are required to maintain either 2,000 feet vertical separation or 5 miles horizontal separation between aircraft. At flight levels below 29,000 feet with aircraft under IFR conditions, ATCSs are required to maintain either 1,000 feet vertical separation or 5 miles horizontal separation. This study focused on data gathered from Air Route Traffic Control Centers (ARTCCs), also called en route facilities.

The first purpose of this study was to examine the relationship between the level of severity (degree of loss of vertical and horizontal separation between aircraft) and air traffic controller workload, measured by the number of aircraft being worked and complexity level reported at the time of the occurrence. The analyses of 1965 and 1966 data by Kershner (1968), data from Kinney, Spahn, and Amato (1977), and analyses of subsequent operational error data (Schroeder, 1982, Stager and Hameluck, 1990, and Schroeder and Nye, 1993) found a general trend for an increased percentage of errors under "Light" and "Moderate," as compared to "Heavy" workloads. Schroeder and Nye (1991) also found two measures of workload (number of aircraft being worked and situation complexity) to be highly correlated with each other. Although OEs tend to occur more often under light and moderate workloads, it was hypothesized that the more severe OEs occur under heavy workload conditions.

The second purpose was to determine which of the "causal factors" attributed to the air traffic controller tended to be associated with OE severity. The general categories of causal factors include: Data Posting, Radar Display, Coordination, Communication, and Position Relief Briefing. Each of these factors is subdivided into more specific categories, with 5-15 subcategories under each main factor. It was hypothesized that the OEs involving the causal factor categories more closely related to the ATCS's situation awareness were more likely to result in greater severity, that is, more serious separation errors. Another variable (not defined as a causal factor) reported on the OE form addresses whether or not the ATCS was aware the error was developing. This factor was included in the analyses, since it relates directly to the hypothesis.

The third purpose of this study was to determine the relationship between the severity of an OE and two of the flight characteristics of the aircraft involved in the errors: aircraft profile and altitude. It was hypothesized that aircraft in a climbing or descending profile are more likely to be involved in the more severe OEs, due to the rapidly changing dynamics of the control situation. It was also hypothesized that aircraft at lower altitudes, where less separation is required, are more likely to be involved in the more severe OEs.

The fourth purpose of this study was to determine how these variables are distributed among individual ARTCCs. It was hypothesized that clusters of facilities could be determined in regard to certain factors related to OE severity.

The fifth purpose of the study was to determine what factors operated during a "major" OE. Since there were only 15 major OFs in the database during the time-frame of this study, only frequencies of the factor categories occurring during a major error were reviewed.

METHOD

Operational Error Data Base

Since 1985 the FAA has operated an Operational Error Data Base to track the operational errors reported across the nation's ATC system. Quality Assurance personnel at each facility are responsible for gathering data and completing a report in accordance with FAA Order 7210.3 (Facility Operation and Administration). Data are coded and entered into the operational error computerized data base, which is under the purview of the Office of Aviation Safety. Since 1988, the data base has included a more detailed encoding of the "causal factor" information. Therefore, for the purposes of this report, the sample includes the error reports for the years 1988, 1989, 1990, and approximately two-thirds of the OEs from 1991, which included information on ATCS causal factors and workload, along with OE severity.

Error Severity

The severity of an OE is categorized and reported by the FAA according to the closest proximity of aircraft, in terms of both horizontal and vertical distances. Table 1 shows the separation parameters and corresponding point assignments, which are added to determine whether the severity was "major," "moderate," or "minor." This calculation is made by a sub-routine of the OE data base. Of the 1053 errors in our sample, only 15 were coded as "major" errors, defined as being less than 0.5 miles horizontal separation AND less than 500 feet vertical separation. Meeting this criterion is the only way that an error can be rated "major," whereas there are many ways that an error can be rated "minor" or "moderate." Some of the key points regarding the separation standards can be summarized as follows:

a) a "major" error is defined as less than 0.5 miles horizontal separation AND less than 500 feet vertical separation between aircraft at the time of occurrence;

b) the designation of "moderate" or "minor" error is based on the determination of the altitude of occurrence:

1) at 29,000 ft (FL 290) or below, a moderate error can involve a range of separation parameters from less than 0.5 miles horizontal combined with up to 900 feet vertical at one extreme, compared to almost 3.0 miles horizontal combined with less than 500 feet vertical. A minor error can involve less than 0.5 miles horizontal separation only if vertical separation is 900 feet or greater. Also, an error can be classified as minor with less than 500 feet vertical separation only if the aircraft were 3.0 miles or farther apart.

2) above FL 290, a moderate error can involve less than 0.5 miles horizontal combined with up to 1000 feet vertical (compared to 900 ft. at FL 290 or lower). At this flight level, while severity points are added for vertical separa-r·on up to 2,000 feet, all errors occurring with vertical separation of 1,000 ft. or greater are classified as minor.

Of the 15 "major" errors, 7 resulted in the filing of a near mid-air collision report by at least one of the involved pilots. Since, for the above reasons, the FAA has categorized these errors as qualitatively different from the other errors, and because there were so few of them, they were analyzed separately, with only frequency data presented in this report.

Air Traffic Controller Workload and Causal Factors

The two measures of workload reported in the OE data base are the number of aircraft being worked by the air traffic controller at the time of the error and a rating of the air traffic complexity, which is an estimation by the quality assurance specialist of the difficulty of the job tasks, based on factors such as weather, airspace restrictions, and variety of duties. The complexity rating is made on a 5-point scale with anchors 1 = "easy," 3 = "average," and 5 = "complex."

TABLE 1
DEFINITION OF SEVERITY CATEGORIES

VERTICAL SEPARATION	POINTS
If occurrence was at or below altitude of 29,000 ft. (FL 290):	
Less than 500 feet	10
500 feet to 600 feet	9
600 feet to 700 feet	8
700 feet to 800 feet	6
800 feet to 900 feet	4
900 feet to 1,000 feet	2
If occurrence was above altitude of 29,000 ft. (FL 290):	
Less than 500 feet	10
500 feet to 700 feet	9
700 feet to 1,000 feet	8
1,000 feet to 1,500 feet	3
1,500 feet to 2,000 feet	2

HORIZONTAL SEPARATION	POINTS
Less than 1/2 mile	10
1/2 mile to 1 mile	8
1 mile to 1 1/2 miles	7
1 1/2 miles to 2 miles	6
2 miles to 2 1/2 miles	5
2 1/2 miles to 3 miles	4
3 miles to 3 1/2 miles	3
3 1/2 miles to 4 miles	2
4 miles to 5 miles	1

SEVERITY
20 points = Major
14-19 points = Moderate
13 or less points = Minor

The causal factors attributed to the ATCS comprise a hierarchy of specific elements within more general categories, as shown in Table 2. For example, if a computer entry had been incorrectly updated (causal factor 1a.1) then that error also involved the less specific category of Data Posting. An operational error can involve multiple causal factors. For this study, an error was coded as 1 if a factor was recorded, and 0 if it was not. Table 2 also includes the percentage of the 1053 errors that involved each factor. It should also be mentioned that sometimes the more global categories were not recorded, while at other times, only the global categories were recorded. For example, in this study, if computer entry error was reported as a factor in an OE, that occurrence was also coded as having involved data posting as a causal factor.

Aircraft Profile Characteristics

One of six possible combinations of aircraft flight characteristics was identified for each error in the sample. The profiles were as follows:

1) all aircraft were climbing,
2) all aircraft were descending,
3) all aircraft were at level flight,
4) one (or more) aircraft was descending and one (or more) aircraft climbing,
5) one (or more) aircraft was at level flight and one (or more) aircraft climbing,
or
6) one (or more) aircraft was at level flight and one (or more) aircraft descending.

RESULTS

Factor Relationships to OE Severity

Since OE severity is differentially defined for aircraft above or below 29,000 feet, the following results are presented in terms of that distinction. As shown in Table 3, the average number of aircraft being worked at the time of the OEs ranged from 8.10 for minor errors at flight levels of 29,000 feet or below (FL 290-) to 10.59 for moderate errors at flight levels above 29,000 feet (FL 290+). The number of aircraft being worked was

Table 2
Percentages of "Minor" or "Moderate" Errors at En Route Facilities that Involved Each Causal Factor

1. Data posting	13
a. Computer entry	6
(1) Incorrect input	2
(2) Incorrect update	1
(3) Premature termination of data	1
(4) Other	2
b. Flight progress strip	9
(1) Not prepared	0
(2) Not updated	3
(3) Posted incorrectly	0
(4) Reposted incorrectly	0
(5) Updated incorrectly	2
(6) Sequenced incorrectly	0
(7) Resequenced incorrectly	0
(8) Interpreted incorrectly	2
(9) Premature removal	0
(10) Other	3
2. Radar display	59
a. Misidentification	14
(1) Overlapping data blocks	3
(2) Acceptance of incomplete or difficult to correlate position info	1
(3) Improper use of identifying turn	0
(4) Failure to reidentify aircraft when accepted target identity becomes questionable	1
(5) Failure to confirm aircraft identity after accepting a radar handoff	0
(6) Other	11
b. Inappropriate use of displayed data	47
(1) Conflict alert	2
(2) Quick look	0
(3) Mode C	12
(4) MSAW/EMSAW	0
(5) Other	37
3. Communications error	36
a. Phraseology	3
b. Transposition	5
c. Misunderstanding	4
d. Readback	20
(1) Altitude	14
(2) Clearance	3
(3) Identification	4
e. Acknowledgment	5
f. Other	8
4. Coordination	15
a. Area of occurrence	
(1) Inter-position	2
(2) Intra-position	3
(3) Inter-sector	4
(4) Inter-facility	2
b. An aircraft penetrated designated airspace of another position of operation or facility without prior approval	4
c. Coordination was effected and controller(s) did not utilize information exchanged	6
(1) Aircraft identification	0
(2) Altitudes/Flight Level	2
(3) Route of flight	1
(4) Clearance limit	0
(5) Speeds	0
(6) APREQS	0
(7) Special instructions	0
(8) Other	2
5. Position relief briefing deficiencies noted	3
a. Employee did not use position relief checklist	1
b. Employee being relieved gave incomplete briefing	1
c. Relieving employee did not make use of pertinent data exchanged at briefing	1
d. Other	1

Note: 0 indicates < .5%

Table 3
Air Traffic Controller Workload and Severity of Operational Errors

	SEVERITY				
	MINOR	*N*	MODERATE	*N*	
# of Aircraft Worked	8.35	737	8.50	315	
FL ≤ 290	8.10	487	8.25	281	Flt. Level $F_{1,1048}$=13.9; p<.001
FL > 290	8.83	250	10.59	34	Severity $F_{1,1048}$=2.2; NS
Traffic Complexity Rating	3.02	737	3.09	315	
FL ≤ 290	3.03	487	3.01	281	Flt. Level $F_{1,1048}$=.06; NS
FL > 290	3.06	250	3.29	34	Severity $F_{1,1048}$=.93; NS

Note: FL = flight level, 290 = 29,000 feet

Table 4
Severity Classification within each Complexity Rating

TRAFFIC COMPLEXITY	MODERATE SEVERITY %	MINOR SEVERITY %	*N*
Easy	27.2	72.8	103
Below Average	29.9	70.1	197
Average	28.5	71.5	376
Above Average	32.7	67.3	306
Complex	31.0	69.0	71
Overall	30.0	70.0	1053

Note: $X^2_{(4)}$=1.89; NS. The *N* represents the number of OEs that occurred in each complexity category.

not significantly different between severity levels ($F_{1,1048}$=2.2, NS), while the number of aircraft being worked was significantly greater ($F_{1,1048}$=13.9, p<.001) at FL 290+. The average air traffic complexity rating was not significantly different between the severity categories ($F_{1,1048}$=.93, NS) or flight levels ($F_{1,1048}$=.06, NS). Similarly, a chi-square test suggested no significant difference in air traffic complexity rating across OE severity categories, (X^2_4=1.89, NS). As indicated in Table 4, the percentages of errors that were moderate (30.0% overall), compared to minor, were relatively consistent, regardless of the traffic complexity. Specifically, 27.2% of the OEs that occurred under the "easy" complexity rating were classified as moderate in severity, while 31.0% of the OEs that were evaluated as occurring under "complex" conditions resulted in a moderately severe OE.

The error causal factors that were differentially related to OE severity are shown in Table 5. The number of cases in each category in Table 5 equals the total number of errors (both minor and moderate in severity) that involved either a given causal factor or ATCS awareness that the error was developing. The percentages represent the proportion of the OEs that were moderately severe for each causal factor. The factors that were associated (determined by using X^2_1=p<.01 as the criterion level) with a lower percentage (compared to 30% of all OEs) of moderate errors included: a) the Misuse of Displayed Data - excluding use of Conflict Alert, and b) awareness by the control-

TABLE 5
PERCENTAGES OF ERRORS THAT WERE MODERATELY SEVERE BY CAUSAL FACTOR AND ATCS AWARENESS

	OVERALL		FL≤290		FL>290	
	% MODERATE	*N*	% MODERATE	*N*	% MODERATE	*N*
Factors Involved with Greater Severity						
Misuse - Conflict Alert	52.0	25	60.0	20	20.0	5
Communications	36.9	379	45.0	300	6.3	79
Readback	40.8	206	47.9	169	8.1	37
Readback - Altitude	41.1	151	46.5	127	12.5	24
Coordination	38.5	161	42.7	110	28.0	51
Inter-facility Coordination	53.8	26	60.0	20	33.3	6
Factors Involved with Lesser Severity						
Misuse of Displayed Data (excluding conflict alert)	22.0	473	27.9	323	9.3	150
ATCS Aware Error was Developing	21.0	267	26.0	177	11.1	90

Note: All of the causal factors above were significant at $p \leq .01$ on chi-square tests.
N= the number of OEs that were related to each factor.
%= the percentage of each *N* that was moderate (compared to minor) in severity.
FL= flight level, 290=29,000 feet.

TABLE 6
DIFFERENCES IN HORIZONTAL SEPARATION BETWEEN AIRCRAFT WHEN OPERATIONAL ERROR INVOLVED CERTAIN CAUSAL FACTORS AND ATCS AWARENESS

	HORIZONTAL SEPARATION					
	OVERALL		FL≤290		FL>290	
	MILES	*N*	MILES	*N*	MILES	*N*
Factors Involved with Greater Severity						
Misuse - Conflict Alert	-.31	25	-.34	20	-.15	5
Communications	-.25	379	-.28	300	-.16	79
Readback	-.30	206	-.27	169	-.39	37
Readback - Altitude	-.29	151	-.25	127	-.43	24
Coordination	-.25	161	-.20	110	-.32	51
Inter-facility Coordination	-.42	26	-.43	20	-.41	6
Factors Involved with Lesser Severity						
Misuse of Displayed Data (excluding conflict alert)	.34	473	.33	323	.37	150
ATCS Aware Error was Developing	.28	267	.33	177	.13	90

Note: The values presented are mean differences in horizontal separation in miles for errors that involved a given causal factor versus all other errors. Negative values represent less separation at occurrence while positive values indicate greater separation.
N=number of OEs that were related to each factor.

Table 7
Percentages of Errors that were Moderately Severe by Profile of Aircraft

	OVERALL		FL≤290		FL>290	
	% MODERATE	*N*	% MODERATE	*N*	% MODERATE	*N*
Profile of Aircraft						
All Climbing	21.9	32	23.3	30	0.0	2
Level & Climbing	26.3	323	34.4	218	9.5	105
Descending & Climbing	28.0	75	31.1	61	7.7	13
Level & Descending	30.3	469	37.6	346	9.8	123
All Descending	34.5	58	36.5	52	16.7	6
All Level	43.0	86	52.9	51	28.6	35

Note:
N= the number of OEs that occurred in each aircraft profile
%= the percentage of each *N* that was classified as moderately severe
FL= flight level, 290=29,000 feet

ler that the error was developing. Twenty-two percent of the 473 OEs that involved Misuse of Displayed Data resulted in a moderately severe error, and similarly, 21% of the 267 OEs in which the ATCS was aware of the developing situation resulted in errors of moderate severity. By contrast, other causal factors were more likely to result in moderate severity. In particular, over 50% of errors that involved Misuse of Conflict Alert or Inter-facility Coordination were classified as moderate. Another factor related to a greater loss of separation was Readback (a communication during which the ATCS fails to detect a pilot's incorrect response to a clearance provided by the ATCS) and more specifically, "Readback involving altitude information." When Readback was a causal factor, over 40% of those errors were classified as moderately severe.

Table 6 lists the differences in average horizontal separation (overall, and at FL 290- or FL 290+) between those errors that involved each of the causal factors in Table 5 versus those that did not. For example, for the errors in which Misuse of Displayed Data (excluding use of Conflict Alert) was involved, the average horizontal separation between aircraft was .34 miles greater than the OEs that did not involve this causal factor. By contrast, in the OEs in which Readback was a factor, the resultant horizontal separation was .30 miles less than the OEs that did not involve Readback. We found that vertical separation was not significantly related to any of the factors. Thus, the impact of these factors in terms of OE severity category, as illustrated in Table 5, was found to be related primarily to the horizontal separation parameter.

Table 7 examines the relationships between aircraft profile, in conjunction with flight levels, and OE severity. Tests of significance were not conducted, due to low expected values in some cells; however, the results are presented for descriptive purposes. Most OEs in the overall sample occurred when one or more aircraft were level and a) others were climbing (*N*=323, 31.0%), or b) others were descending (*N*=469, 45.0%). Surprisingly, the greatest likelihood for moderate severity occurred when all aircraft were at "level" flight (43.0% overall); 52.9% at FL 290-, and 28.6% at FL 290+. Also, flight level was related to severity for each aircraft profile; i.e., a greater percentage of OEs were moderately severe at FL 290-, compared with FL 290+.

Table 8
Average ATCS Workload During Moderately Severe OEs at En Route Facilities

Facility	*N*	# Aircraft Worked	Traffic Complexity		% ATCS Awareness
ZAB	9	10.00	3.33	(2)	22
ZAU	31	7.68	2.77	(1)	0
ZBW	19	5.79	2.74	(1)	11
ZDC	35	9.09	3.71	(2)	23
ZDV	11	9.27	3.73	(2)	36
ZFW	16	9.31	3.31	(2)	6
ZHU	13	8.92	3.31	(2)	15
ZID	23	9.30	3.13	(2)	4
ZJX	20	8.20	2.50	(1)	20
ZKC	9	10.00	3.78	(2)	33
ZLA	15	7.00	2.60	(1)	20
ZLC	4	11.25	3.25	(2)	75
ZMA	11	8.64	3.09	(2)	18
ZME	10	10.60	3.30	(2)	10
ZMP	5	8.60	3.20	(2)	0
ZNY	26	6.88	2.77	(1)	31
ZOA	11	7.45	2.82	(1)	36
ZOB	19	9.26	3.00	(2)	21
ZSE	6	7.33	2.67	(1)	17
ZTL	9	8.33	3.78	(2)	11
Overall					
Mean		8.65	3.14		21
SD		1.35	.40		

Note: The number in ( ) represents a classification of each facility as either relatively high ATCS workload (2) or low workload (1) reported at the time of the moderately severe OEs. Awareness= the percentage of each facility's moderately severe OEs in which the ATCS was aware that the error was developing.

Facility-level characteristics of moderately severe OEs

Tables 8 through 10 illustrate the results of analyses by facility for the moderately severe errors at ARTCC facilities located in the continental U.S., i.e. excluding ZSU, ZHN, and ZAN. Only moderately severe errors (excluding minor OEs) are reported here because of their greater salience for aviation safety and our finding of nonsignificant associations between workload and OE severity. Table 8 lists the average number of aircraft being worked and air traffic complexity rating. The results of a series of cluster analyses produced two interpretable groups of facilities based on reported ATCS workload. Each of the relatively low workload facilities (ZAU, ZBW, ZJX, ZLA, ZNY, ZOA, and ZSE) was characterized by an average air traffic complexity rating of less than 3.0 ("average") combined with 8.2 or fewer aircraft being worked. It should be noted that some degree of variability could be expected, given potential differences in reporting standards and practices, not only between facilities but within a facility as well. Table 8 also illustrates facility differences in the percentages of moderately severe errors in which the ATCS was aware that the error was developing. Specifically, ZAU and ZMP reported that no ATCS was aware of the developing error in any of their OEs. By contrast, several facilities (ZDV, ZKC, ZLC, and ZOA) reported that the ATCS was cognizant of the situation prior to loss of separation in one-third or more of their moderately severe OEs.

TABLE 9
CAUSAL FACTORS ASSOCIATED WITH MODERATELY SEVERE OEs AT EN ROUTE FACILITIES (% OF ERRORS)

FACILITY	DISPLAYED DATA	CONFLICT ALERT	READBACK	READBACK-ALTITUDE	INTER-FACILITY COORDINATION
ZAB	22	11	33	22	00
ZAU	32	03	32	26	00
ZBW	32	16	21	11	05
ZDC	43	00	20	14	00
ZDV	27	00	27	27	00
ZFW	38	06	25	25	13
ZHU	23	08	46	31	00
ZID	35	00	30	30	09
ZJX	25	15	20	20	05
ZKC	11	00	44	22	00
ZLA	33	00	27	13	07
ZLC	100	00	00	00	00
ZMA	27	09	09	09	00
ZME	20	00	30	20	20
ZMP	40	20	00	00	00
ZNY	23	04	19	15	12
ZOA	27	00	45	09	18
ZOB	26	00	32	26	00
ZSE	33	00	33	33	00
ZTL	44	00	33	11	00
Overall	33	05	26	18	04

Note: The data are the percentages of a facility's moderately severe OEs that involved these causal factors.

To examine ATCS workload in conjunction with awareness that the error was developing, multidimensional scaling (MDS) was applied, with the results shown in Figure 1. First, the two workload measures and ATCS awareness data were aggregated at the facility level. Then the "*z*" score values for number of aircraft being worked and traffic complexity were summed to compute a composite measure representing the average ATCS workload at the time of OE occurrence for each facility. A dissimilarity matrix among facilities was created based on Euclidean distances using the composite workload and error awareness variables. The matrix was then analyzed using the classical MDS approach, in which the cases (en route facilities) were plotted in two dimensions. Thus, MDS provided a "geometric" representation of the facilities similarity/dissimilarity in terms of workload and ATCS awareness. Dimension 1 geometrically represents ATCS workload, while dimension 2 is ATCS awareness that the error was developing. The intersection of the dimensions produced four quadrants into which facilities were grouped, based on their relative similarity/dissimilarity among each other. Quadrant 1 was defined by relatively high ATCS workload combined with greater than average error awareness. This high workload- greater awareness condition was illustrated best by ZDV, ZLC, and ZKC. The high workload-less awareness facilities (Quadrant 2) included ZFW, ZTL, and ZME. ZAU and ZBW were characterized by relatively low ATCS workload combined with less

TABLE 10
PROFILE OF AIRCRAFT IN MODERATELY SEVERE OEs AT EN ROUTE FACILITIES

FACILITY	ALL CLIMB	DESCEND CLIMB	ALL DESCEND	LEVEL CLIMB	LEVEL DESCEND	ALL LEVEL
ZAB	.0	.0	22.2	.0	77.8	.0
ZAU	.0	6.5	.0	22.6	61.3	9.7
ZBW	.0	15.8	5.3	21.1	52.6	5.3
ZDC	2.9	2.9	5.9	20.6	58.8	8.8
ZDV	.0	.0	9.1	36.4	45.5	9.1
ZFW	.0	.0	.0	37.5	43.8	18.8
ZHU	7.7	.0	23.1	30.8	30.8	7.7
ZID	4.5	13.6	4.5	31.8	13.6	31.8
ZJX	.0	5.0	5.0	20.0	60.0	10.0
ZKC	.0	.0	.0	55.6	33.3	11.1
ZLA	.0	.0	.0	33.3	46.7	20.0
ZLC	.0	25.0	25.0	.0	25.0	25.0
ZMA	9.1	18.2	.0	27.3	36.4	9.1
ZME	.0	.0	.0	50.0	50.0	.0
ZMP	.0	.0	20.0	40.0	20.0	20.0
ZNY	3.8	7.7	7.7	30.8	46.2	3.8
ZOA	.0	20.0	.0	20.0	40.0	20.0
ZOB	5.3	5.3	5.3	31.6	42.1	10.5
ZSE	.0	.0	16.7	33.3	50.0	.0
ZTL	.0	11.1	11.1	22.2	44.4	11.1
Overall	1.7	6.6	8.0	28.2	43.9	11.6

Note: The data are percentages of a facility's moderately severe OEs that occurred under the various aircraft profiles.

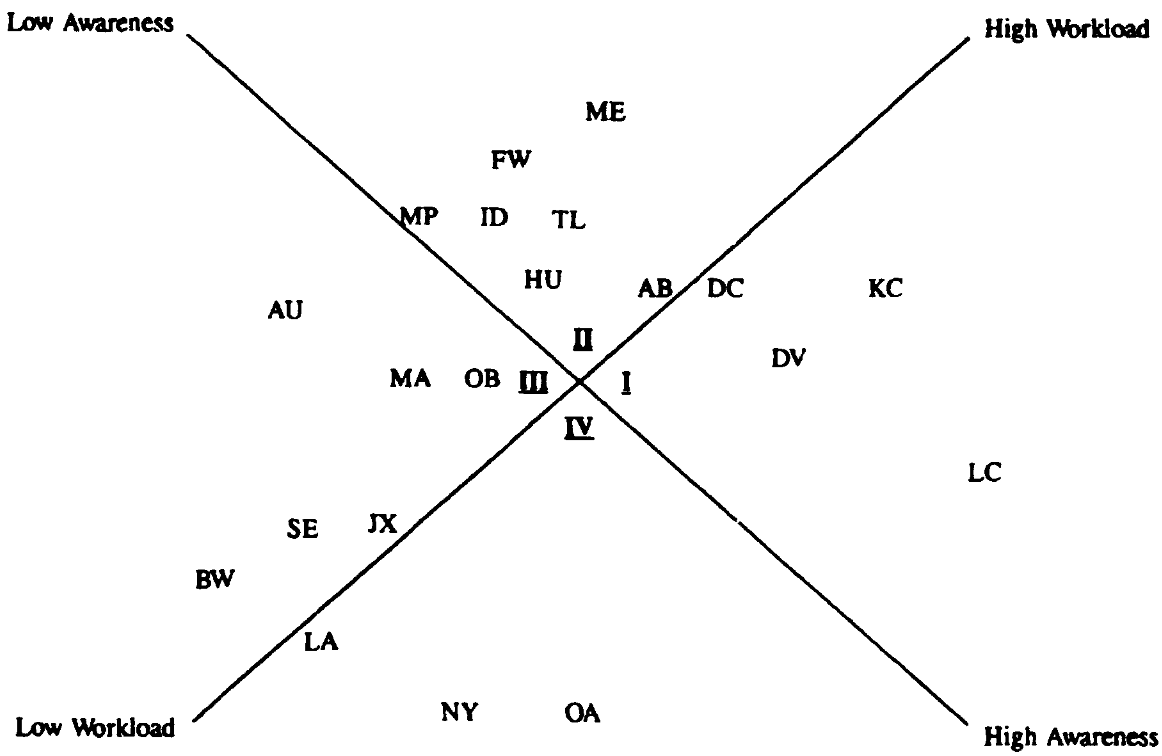
awareness (Quadrant 3), while ZNY and ZOA reported relatively low ATCS workload combined with greater awareness (Quadrant 4).

There was also considerable variability in the frequency of the causal factors previously found to be related to severity. For example, the percentages of OEs that involved Misuse of Displayed Data ranged from 11% to 44% across facilities (Table 9). Similarly, while Readback was involved in 26% of all moderately severe OEs, at the facility level, between 0% and 46% of the OEs involved Readback as a factor.

Table 10 illustrates the percentages of moderately severe OEs that occurred under the various aircraft profile categories described previously. The most frequent profile - aircraft level and aircraft descending - characterized over 40% of the OEs with a range of 13.6% to 77.8% across facilities. The "All level" aircraft profile was present between 0% and 31.8% depending on facility.

Overall these results illustrate why future research regarding operational errors should measure facility-level differences to estimate the extent to which findings are generalizable among ARTCCs. It would be interesting to investigate the relationships that may exist between these facility-level differences and facility differences in traffic density, local procedures, and airspace configuration.

Figure 1
Multidimensional Scaling of En Route Facilities based on Workload and Situation Awareness Characteristics at the Time of the OEs



Note:
Quadrant I = high workload - high awareness
Quadrant II = high workload - low awareness
Quadrant III = low workload - low awareness
Quadrant IV = low workload - high awareness
Workload = standardized levels for number of aircraft being worked plus air traffic complexity at the time of the OEs
Awareness = ATCS awareness that the OE was developing

TABLE 11
FREQUENCY OF CAUSAL FACTOR CATEGORIES THAT RESULTED IN "MAJOR" ERRORS AT EN ROUTE FACILITIES

1. Data posting 5
   a. Computer entry 2
      (1) Incorrect input 2
      (2) Incorrect update 1
      (3) Premature termination of data 1
      (4) Other 2
   b. Flight progress strip 4
      (1) Not prepared 0
      (2) Not updated 3
      (3) Posted incorrectly 0
      (4) Reposted incorrectly 0
      (5) Updated incorrectly 2
      (6) Sequenced incorrectly 0
      (7) Resequenced incorrectly 0
      (8) Interpreted incorrectly 1
      (9) Premature removal 0
      (10)Other 1

2. Radar display 9
   a. Misidentification 2
      (1) Overlapping data blocks 3
      (2) Acceptance of incomplete or difficult to correlate position info. 1
      (3) Improper use of identifying turn 0
      (4) Failure to reidentify aircraft when accepted target identity becomes questionable 1
      (5) Failure to confirm aircraft identity after accepting a radar handoff 0
      (6) Other 2
   b. Inappropriate use of displayed data 7
      (1) Conflict alert 2
      (2) Quick look 0
      (3) Mode C 1
      (4) MSAW/EMSAW 0
      (5) Other 7

3. Communications error 6
   a. Phraseology 3
   b. Transposition 1
   c. Misunderstanding 1
   d. Readback 2
      (1) Altitude 1
      (2) Clearance 3
      (3) Identification 1
   e. Acknowledgment 2
   f. Other 1

4. Coordination 6
   a. Area of occurrence
      (1) Inter-position 1
      (2) Intra-position 3
      (3) Inter-sector 2
      (4) Inter-facility 1
   b. An aircraft penetrated designated airspace of another position of operation or facility without prior approval 1
   c. Coordination was effected and controller(s) did not utilize information exchanged 5
      (1) Aircraft identification 1
      (2) Altitudes/Flight Level 1
      (3) Route of flight 1
      (4) Clearance limit 0
      (5) Speeds 0
      (6) APREQS 0
      (7) Special instructions 1
      (8) Other 2

5. Position relief briefing deficiencies noted 1
   a. Employee did not use position relief checklist 1
   b. Employee being relieved gave incomplete briefing 1
   c. Relieving employee did not make use of pertinent data exchanged at briefing 1
   d. Other 1

Characteristics of OEs of Major Severity

Six of the 15 OEs categorized as "major" had a complexity rating of "above average," while four were classified as having occurred under "average" conditions, two had a "below average" rating, and 3 had an "easy" rating; producing a mean complexity rating of 2.87. The average number of aircraft being worked was 8.47 with the range between 2 and 15. These findings illustrate the sizable variability in ATCS workload conditions found during the OEs classified as "major" in this study.

Regarding the flight characteristics of the aircraft in the major OEs, three of the OEs occurred at FL 290+. In five cases, all of the aircraft involved were in a level profile, in seven the aircraft were level and descending, in one OE the profile was level and climbing, and two occurred when aircraft were descending and climbing.

Table 11 shows the frequencies of the causal factors that resulted in OEs that were rated "major" in severity. The Data Posting factor was involved in five OEs, Radar Display in nine, Communications in six, Coordination in five, and Relief Briefing in one OE. (As noted previously, an OE can involve multiple causal factors).

DISCUSSION

General Findings

A counter-intuitive finding of this study was that neither a quantitative measure of air traffic controller workload (number of aircraft being worked) nor a rating of air traffic complexity was found to be related to OE severity. Future research could examine the correspondence between these "objective" workload measures and "subjective" workload assessments made with instruments such as the National Aeronautics and Space Administration Task Load Index (Hart & Staveland, 1988) in order to expand the understanding of the workload conditions of air traffic controllers.

Causal factors that relate to ATCS awareness would likely include those that are not easily corrected if not caught immediately, allowing the error situation to build until it is too late to avoid. In general, the causal factors that resulted in a greater loss of separation were those which would likely reduce awareness of the situation by the air traffic controller (i.e. inter-facility coordination, incorrect readback of altitude by pilot, etc.). This assertion is supported by the finding that if the ATCS was aware the error was developing, the errors tended to be less severe. Additionally, the misuse of displayed data (excluding conflict alert) was associated with less severity, which suggests that the factors associated with severe errors have an insidious nature that is not characteristic of errors that involve the misuse of displayed data.

It is interesting to note that, for each factor, only the horizontal separation parameter, not vertical separation, was significantly affected. This may be because altitude, used to provide vertical separation, is reported numerically in the data block. Thus, altitude information is likely to be much more salient than the information used to make a judgment of the extent of horizontal separation between aircraft. Judgment of horizontal separation is based on the visual distance in separation between two targets on the plan view display and judgments of their relative speed. However, ATCSs may also prefer to use the horizontal parameter to achieve separation, thereby resulting in a difference that is based primarily on frequency of usage.

Although most operational errors occur when at least one aircraft is in level flight and at least one aircraft is either descending or ascending, the "All Level" aircraft profile was found to be associated with a greater percentage of moderately severe operational errors. Perhaps less attention is directed to aircraft in the "All Level" profile, resulting in a greater likelihood of severe errors. Additionally, moderately severe errors were more likely to occur at FL $\leq$ 290. However, at FL $\leq$ 290, when aircraft are in an "All Level" profile, they typically are flying at faster speeds and thus, separation can be lost more rapidly, potentially resulting in a greater loss of separation between aircraft.

It should be borne in mind that these are national averages and the values are different for certain facilities. Differences in traffic density, local procedures, and airspace configuration may limit the ability to generalize these results across different facilities. This is evidenced by the results of the facility level analyses presented earlier. Furthermore, without additional information concerning the percentage of time ATCSs at the various facilities spend controlling traffic under the various complexity or workload conditions it is difficult to determine the primary factors associated with these outcomes.

Facility Level Findings

Although neither the number of aircraft being worked nor a rating of air traffic complexity was found to be related to OE severity, a series of cluster analyses produced two interpretable groups of facilities based on reported ATCS workload. This measure, which for low ATCS workload was characterized by an average air traffic complexity rating of less than 3.0 ("average") combined with 8.2 or fewer aircraft being worked, was used to examine ATCS workload in conjunction with situation awareness.

Several hypotheses of the effect of workload on situation awareness are offered. The first suggests that awareness decreases as workload increases. This might be due to difficulty in maintaining an accurate mental picture of the air traffic situation as its complexity and/or information load increases. This phenomena is more likely to operate under very high workload conditions. Another possibility suggests that, as workload shifts from a high to low level, awareness decreases. This situation is likely to exist after a busy traffic "push". Additionally, awareness may decrease if low workload conditions are sustained for an extended period of time. This is more likely to occur during very low workload conditions. Furthermore, a fatigue effect could be operating under sustained periods of high workload, resulting in a decrease in awareness during later periods of a high workload watch.

It appears that reduced situation awareness might occur as an effect of very different workload related causes. In this research, several clusters of facilities were distinguished based on differences along the dimensions of ATCS workload and situation awareness. Facilities were classified as either high workload/high awareness, high workload/low awareness, low workload/high awareness, or low workload/low awareness. The data are not available to determine which of the four hypotheses mentioned above might have been operating during each of the errors analyzed in this study.

Two facilities best exemplified the relatively low workload/low awareness combination (ZAU,ZBW). They accounted for 17% of all the moderately severe errors. However, it was not possible to determine the extent to which these errors were a result of traffic density, airspace configuration, local operating procedures, workstation design, poor technique, or any of a number of other factors. In fact, since normative information is not available on variables such as traffic density, one must settle for a description of the factors associated with operational irregularities.

"Major" OE Severity Findings

Fortunately, over the 31/2 years of data analyzed and presented in this report, only 15 of the 1053 OEs were rated "major" in severity. Causal factor frequencies for the "major" errors proportionately matched the frequencies of the "minor" and "moderate" causal factor categories. Additionally, the average number of aircraft being worked did not differ between severity categories. Furthermore, the profile in which the majority of "minor" and "moderate" errors occurred (level & descending) was also the profile of the majority of the "major" errors. Although 40% of the "major" errors were rated "above average" in complexity, the mean complexity for the "major" errors (2.87) was less than that for the "minor" and "moderate" errors (3.05). However, given the small sample of "major" errors this finding was not statistically significant.

CONCLUSION

The types of analyses presented in this report allow for the identification of factors more likely to precipitate air traffic control operational errors. However, as mentioned earlier, due to the lack of normative data, one must settle for a description of the factors associated with these operational irregularities. Additionally, the reporting process, including the reporting reliability of the investigators, may affect the extent to which these relationships can be determined. For the investigative process to allow for a more definitive determination of the factors involved in operational irregularities, investigators must be able to review the dynamics associated with the air traffic situation.

Currently, Quality Assurance (QA) specialists review multiple printouts of data that detail aircraft locations and ATCS/Host Computer System interactions, as well as multiple audio recordings of pilot/controller and interphone communications to determine events surrounding the occurrence of an operational irregularity. The task of piecing together the "big picture" from multiple sources of data is a difficult and time-consuming part of the QA specialist's job. The reliability of the findings of the QA investigation affect the reliability of the report filed for each irregularity. To allow the QA team to spend more time identifying the sources of problems associated with an incident and less time piecing together the dynamics of the air traffic control situation, a method is required that allows for a re-creation of incidents and integrates the various data sources into a coherent picture. Such a system has been developed that would allow for the collection of normative data and assist in determining more definitively the location and likelihood of breakdowns in the human-machine system (Rodgers & Duke, 1993).

It may be possible to quantify characteristics of the air traffic control situation such as workload, complexity, severity, as well as others as a by-product of the re-creation of incidents using the system mentioned above. This would reduce the variability that appears to exist between investigators and facilities. Standardization of the investigation process in this manner would allow for an improved determination of the factors involved in operational irregularities. Additionally, such a system would provide the capability to collect normative information and potentially allow for more than a descriptive view of these occurrences.

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APPENDIX A

Causal Factor Definitions*

I. Data Posting - A data posting error is any error of calculation, omission, or incomplete data, erroneous entries, handling, or subsequent revisions to this data. This includes errors in posting and recording data. It does not include errors involved in receiving, transmitting, coordinating, or otherwise forwarding this information.

II. Radar Display

A. Misidentification - Radar misidentification means a failure to properly identify the correct target and includes subsequent errors committed after the original identification was properly accomplished. Indicate the listed item(s) most closely describing the reason for misidentification.

B. Inappropriate Use of Displayed Data - A data or display information error occurs due to a failure to maintain constant surveillance of a flight data display or traffic situation and to properly present or utilize the information presented by the display or situation.

III. Communications - A communications error is a causal factor associated with the exchange of information between two or more people (e.g., pilots and specialists). It refers to the failure of human communication not communications equipment.

A. Phraseology - Use of incorrect or improper phraseology.

B. Transposition - Errors due to transposition of words, numbers, or symbols by either oral or written means. This involves writing/saying one thing while thinking/hearing something else.

C. Misunderstanding - The failure to communicate clearly and concisely so that no misunderstanding exists for any actions contemplated or agreed upon.

D. Readback - The failure to identify improper or incorrect readback of information.

E. Acknowledgment - The failure to obtain an acknowledgment for the receipt of information.

IV. Coordination - Any factor associated with a failure to exchange requirement information. This includes coordination between individuals, positions of operation, and facilities for exchange of information such as APREQ's, position reports, forwarding of flight data, etc.

V. Position Relief Briefing - Relief briefing errors are special errors of both communication and coordination that occur as the result of position relief. They include such things as failure to give a relief briefing, failure to request a briefing, incomplete or erroneous briefing, etc.

* These definitions were extracted from FAA Form 7210-3.

☆U.S. GOVERNMENT PRINTING OFFICE: 1994 - 560-063/80101