Human Error Analysis of Commercial Aviation Accidents: Application of the Human Factors Analysis and Classification System (HFACS)

DOUGLAS A. WIEGMANN, PH.D. AND
SCOTT A. SHAPPELL, PH.D.

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Background: The Human Factors Analysis and Classification System (HFACS) is a general human error framework originally developed and tested within the U.S. military as a tool for investigating and analyzing the human causes of aviation accidents. Based on Reason's (1990) model of latent and active failures, HFACS addresses human error at all levels of the system, including the condition of aircrew and organizational factors. The purpose of the present study was to assess the utility of the HFACS framework as an error analysis and classification tool outside the military. ***Methods:*** The HFACS framework was used to analyze human error data associated with aircrew-related commercial aviation accidents that occurred between January 1990 and December 1996 using database records maintained by the NTSB and the FAA. ***Results:*** Investigators were able to reliably accommodate all the human causal factors associated with the commercial aviation accidents examined in this study using the HFACS system. In addition, the classification of data using HFACS highlighted several critical safety issues in need of intervention research. ***Conclusion:*** These results demonstrate that the HFACS framework can be a viable tool for use within the civil aviation arena. However, additional research is needed to examine its applicability to areas outside the flight deck, such as aircraft maintenance and air traffic control domains.

Keywords: Aviation safety, accident investigation, commercial aviation.

HUMANS, by their very nature, make mistakes; therefore, it should come as no surprise that human error has been implicated in a variety of occupational accidents, including 70% to 80% of those in civil and military aviation (9,23,25). In fact, while the number of aviation accidents attributable solely to mechanical failure has decreased markedly over the past 40 yr, those attributable at least in part to human error have declined at a much slower rate (15). Given findings such as these, it would appear that interventions aimed at reducing the occurrence or consequences of human error have not been as effective as those directed at mechanical failures. Clearly, if accidents are to be reduced further, more emphasis must be placed on the genesis of human error as it relates to accident causation.

Background

The prevailing means of investigating human error in aviation accidents today remains the analysis of accident and incident data. Unfortunately, most accident reporting systems are not designed around any theoretical framework of human error. Indeed, most accident reporting systems are designed and employed by engineers and front-line operators with only limited backgrounds in human factors. As a result, these systems have been useful for identifying engineering and mechanical failures but relatively ineffective and narrow in scope where human error exists. Even when human factors are addressed, the terms and variables used are often ill-defined and archival databases poorly organized. The end results are post-accident databases that are typically not conducive to a traditional human error analysis, making the identification of intervention strategies onerous (22).

The Accident Investigation Process

To illustrate this point further, let us examine the accident investigation and intervention process separately for the mechanical and human components of an accident. Consider first the occurrence of an aircraft system or mechanical failure that results in an accident or injury (**Fig. 1**). An investigation takes place, which includes the examination of objective and quantifiable information, such as the wreckage and flight data recorder, as well as the application of sophisticated analytical techniques like metallurgical tests and computer modeling. This kind of information is then used to determine the probable mechanical cause(s) of the accident and to identify safety recommendations.

On completion of the investigation, this information is typically entered into a highly structured and well-defined accident database. These data can then be pe-

From the Institute of Aviation, University of Illinois at Urbana-Champaign, Savoy, IL (D. A. Wiegmann); and Civil Aerospace Medicine Institute, Federal Aviation Administration, Oklahoma City, OK (S.A. Shappell).

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Address reprint requests to: Douglas A. Wiegmann, Ph.D., who is Assistant Professor of Aviation Human Factors, Aviation Research Lab, University of Illinois at Urbana-Champaign, Savoy, IL 61874; dwiegman@uiuc.edu.

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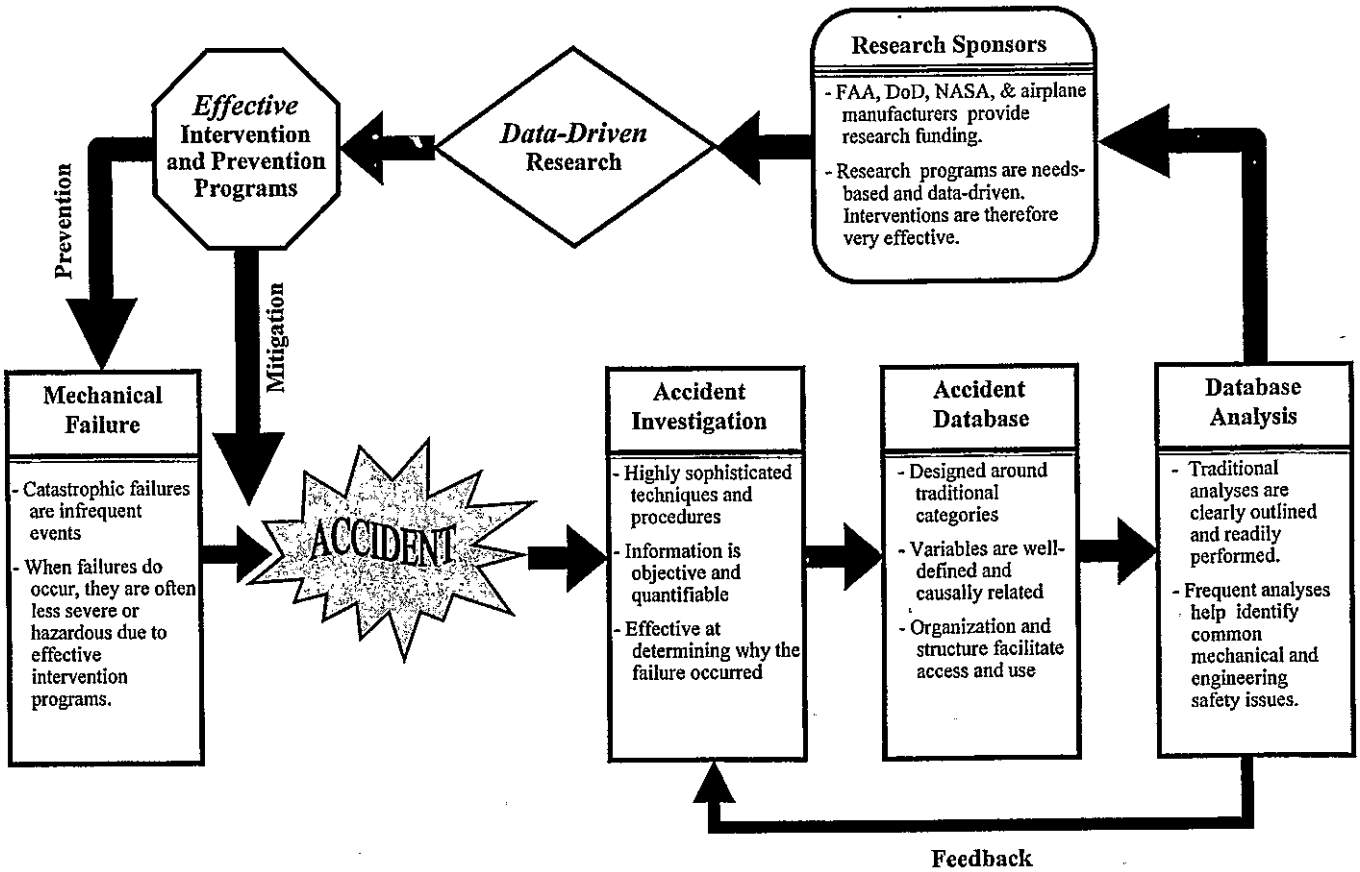

Fig. 1. General process of investigating and preventing aviation accidents involving mechanical or systems failures.

riodically analyzed to determine system-wide safety issues and provide feedback to investigators, thereby improving investigative methods and techniques. In addition, these results are often used to guide organizations (e.g., the Federal Aviation Administration [FAA], National Aeronautics and Space Administration [NASA], Department of Defense [DoD], airplane manufacturers and airlines) in deciding which research or safety programs to sponsor. As a result, these needs-based, data-driven programs, in turn, have typically produced effective intervention strategies that either prevent mechanical failures from occurring altogether, or mitigate their consequences when they do happen. In either case, there has been a substantial reduction in the rate of accidents due to mechanical or systems failures.

In stark contrast, **Fig. 2** illustrates the current human factors accident investigation and prevention process. This example begins with the occurrence of an aircrew error during flight operations that leads to an accident or incident. A human performance investigation then ensues to determine the nature and causes of these errors. However, unlike the tangible and quantifiable evidence surrounding mechanical failures, the evidence and causes of human error are generally qualitative and elusive. Furthermore, human factors investigative and analytical techniques are often less refined and sophisticated than those used to analyze mechanical and engineering concerns. As such, the determination of human factors causal to the accident is a tenuous practice at best; all of which makes the information entered in the accident database sparse and ill-defined.

As a result, when traditional data analyses are performed to determine common human factors problems across accidents, the interpretation of the findings and the subsequent identification of important safety issues are of little practical use. To make matters worse, results from these analyses provide limited feedback to investigators and are of limited use to airlines and government agencies in determining the types of research or safety programs to sponsor. As such, many research programs tend to be intuitively, or fad-driven, rather than data-driven, and typically produce intervention strategies that are only marginally effective at reducing the occurrence and consequence of human error. The overall rate of human-error related accidents, therefore, has remained relatively high and constant over the last several years (15).

Addressing the Problem

If the FAA and the aviation industry are to achieve their goal of significantly reducing the aviation accident rate over the next 10 yr, the primary cause of aviation accidents (i.e., human factors) must be addressed (5). However, as illustrated in Fig. 2, simply increasing the amount of money and resources spent on human factors research is not the solution. Indeed, a great deal of resources and efforts are currently being expended. Rather, the solution is to redirect safety efforts so that they address important human factors issues. However, this assumes one thing, that we *know* what the important human factors issues are. Therefore, before re-

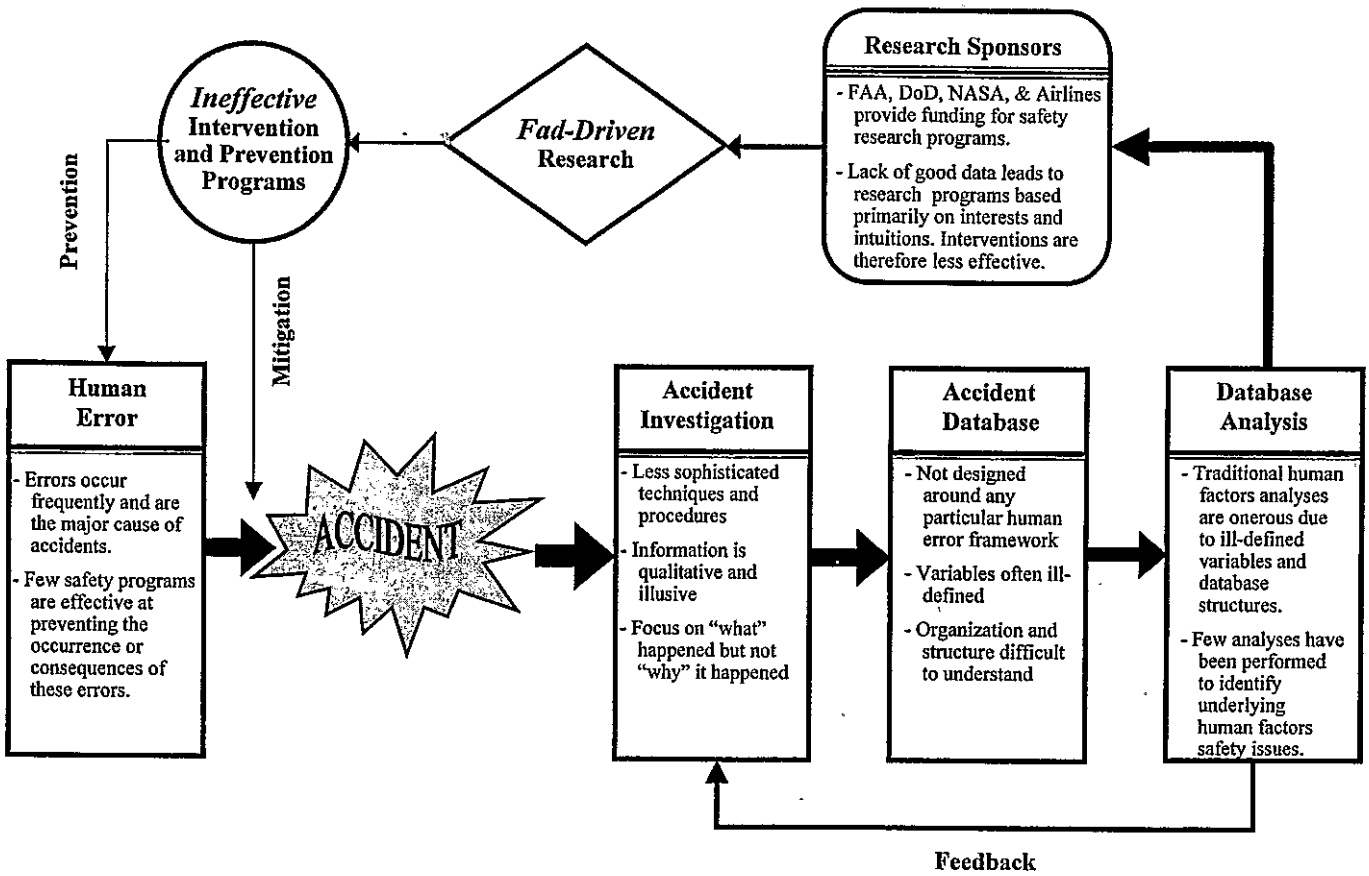

Fig. 2. General process of investigating and preventing aviation accidents involving human error.

search efforts can be systematically refocused, a comprehensive analysis of existing databases needs to be conducted to determine those human factors responsible for aviation accidents and incidents. Furthermore, if these efforts are to be sustained, new investigation methods and techniques will need to be developed so that data gathered during human factors accident investigations can be improved, and analysis of the underlying causes of human error facilitated.

To accomplish this, a general human error framework is needed around which new investigative methods can be designed and existing postaccident databases restructured. Previous attempts to do this have met with encouraging, yet limited, success (9,22). This is due primarily to the fact that performance failures are influenced by a variety of human factors that are typically not addressed by traditional error frameworks. For instance, with few exceptions (e.g., 11), human error taxonomies do not consider the potential adverse mental and physiological condition of the individual (e.g., fatigue, illness, attitudes, etc.) when describing errors in the cockpit. Likewise, latent errors committed by officials within the management hierarchy, such as line managers and supervisors are often not addressed, even though it is well known that these factors directly influence the condition and decisions of pilots (12). Therefore, if a comprehensive analysis of human error is to be conducted, a taxonomy that takes into account the multiple causes of human failure must be offered.

Recently, Human Factors Analysis and Classification System (HFACS) has been developed to meet these needs (16,18,20). This system, which is based on Reason's (1990) model of latent and active failures, was originally developed for the U.S. Navy and Marine Corps as an accident investigation and data analysis tool. Since its original development however, HFACS has been employed by other military organizations (e.g., U.S. Army, Air Force, and Canadian Defense Force) as an adjunct to preexisting accident investigation and analysis systems. To date, the HFACS framework has been applied to over 1,000 military aviation accidents yielding objective, data-driven intervention strategies while enhancing both the quantity and quality of human factors information gathered during accident investigations (20).

Other organizations such as the FAA and NASA have explored the use of HFACS as a complement to preexisting systems within civil aviation in an attempt to capitalize on gains realized by the military (3). Still, few systematic efforts have examined whether HFACS is indeed a viable tool within the civil aviation industry, even though it can be argued that the similarities between military and civilian aviation outweigh their differences. The purpose of the present study was to empirically address this issue by applying the HFACS framework, as originally designed for the military, to the classification and analysis of civil aviation accident data. Before beginning however, a brief overview of the HFACS system will be presented for those readers who may not be familiar with the framework (for a detailed description of HFACS see 18 and 20).

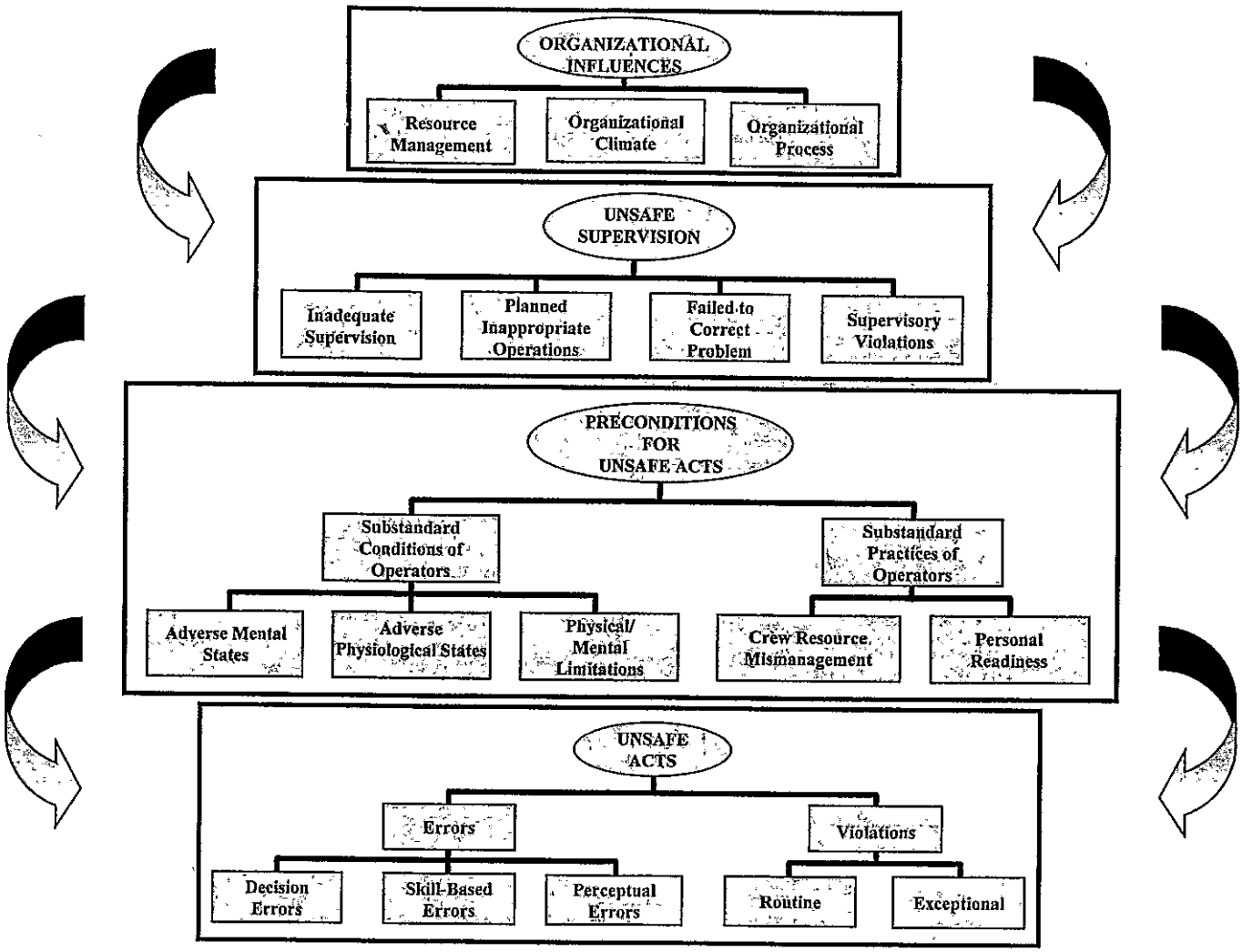

Fig. 3. Overview of the Human Factors Analysis and Classification System (HFACS).

HFACS

Drawing on Reason's (12) concept of latent and active failures, HFACS describes human error at each of four levels of failure: 1) unsafe acts of operators (e.g., aircrew); 2) preconditions for unsafe acts; 3) unsafe supervision; and 4) organizational influences. A brief description of each causal category follows (**Fig. 3**).

Unsafe Acts of Operators

The unsafe acts of operators (aircrew) can be loosely classified into one of two categories: errors and violations (12). While both are common within most settings, they differ markedly when the rules and regulation of an organization are considered. That is, errors can be described as those "legal" activities that fail to achieve their intended outcome, while violations are commonly defined as behavior that represents the willful disregard for the rules and regulations. It is within these two overarching categories that HFACS describes three types of errors (decision, skill-based, and perceptual) and two types of violations (routine and exceptional).

Errors: One of the more common error forms, *decision errors*, represent conscious, goal-intended behavior that proceeds as designed, yet the plan proves inadequate or inappropriate for the situation. Often referred to as "honest mistakes," these unsafe acts typically manifest as poorly executed procedures, improper choices, or simply the misinterpretation or misuse of relevant information.

In contrast to decision errors, the second error form, *skill-based errors*, occur with little or no conscious thought. Just as little thought goes into turning one's steering wheel or shifting gears in an automobile, basic flight skills such as stick and rudder movements and visual scanning often occur without thinking. The difficulty with these highly practiced and seemingly automatic behaviors is that they are particularly susceptible to attention and/or memory failures. As a result, skill-based errors such as the breakdown in visual scan patterns, inadvertent activation/deactivation of switches, forgotten intentions, and omitted items in checklists often appear. Even the manner (or skill) with which one flies an aircraft (aggressive, tentative, or controlled) can effect safety.

While, decision and skill-based errors have dominated most accident databases and have therefore been included in most error frameworks, the third and final

error form, *perceptual errors,* has received comparatively less attention. No less important, perceptual errors occur when sensory input is degraded or "unusual," as is often the case when flying at night, in the weather, or in other visually impoverished environments. Faced with acting on imperfect or less information, aircrew run the risk of misjudging distances, altitude, and decent rates, as well as responding incorrectly to a variety of visual/vestibular illusions.

Violations: Although there are many ways to distinguish between types of violations, two distinct forms have been identified based on their etiology. The first, *routine violations* tend to be habitual by nature and are often enabled by a system of supervision and management that tolerates such departures from the rules (12). Often referred to as bending the rules, the classic example is that of the individual who drives his/her automobile consistently 5–10 mph faster than allowed by law. While clearly against the law, the behavior is, in effect, sanctioned by local authorities (police) who often will not enforce the law until speeds in excess of 10 mph over the posted limit are obtained.

Exceptional violations, on the other hand, are isolated departures from authority, neither typical of the individual nor condoned by management. For example, while driving 65 in a 55 mph zone might be condoned by authorities, driving 105 mph in a 55 mph zone certainly would not. It is important to note, that while most exceptional violations are appalling, they are not considered "exceptional" because of their extreme nature. Rather, they are regarded as exceptional because they are neither typical of the individual nor condoned by authority.

Preconditions for Unsafe Acts

Simply focusing on unsafe acts, however, is like focusing on a patient's symptoms without understanding the underlying disease state that caused it. As such, investigators must dig deeper into the preconditions for unsafe acts. Within HFACS, two major subdivisions are described: substandard conditions of operators and the substandard practices they commit.

Substandard conditions of the operator: Being prepared mentally is critical in nearly every endeavor, perhaps more so in aviation. With this in mind, the first of three categories, *adverse mental states,* was created to account for those mental conditions that adversely affect performance. Principal among these are the loss of situational awareness, mental fatigue, circadian dysrhythmia, and pernicious attitudes such as overconfidence, complacency, and misplaced motivation that negatively impact decisions and contribute to unsafe acts.

Equally important however, are those *adverse physiological states* that preclude the safe conduct of flight. Particularly important to aviation are conditions such as spatial disorientation, visual illusions, hypoxia, illness, intoxication, and a whole host of pharmacological and medical abnormalities known to affect performance. For example, it is not surprising that when aircrew become spatially disoriented and fail to rely on flight instrumentation, accidents can, and often do, occur.

Physical and/or mental limitations of the operator, the third and final category of substandard condition, includes those instances when necessary sensory information is either unavailable, or if available, individuals simply do not have the aptitude, skill, or time to safely deal with it. For aviation, the former often includes not seeing other aircraft or obstacles due to the size and/or contrast of the object in the visual field. However, there are many times when a situation requires such rapid mental processing or reaction time that the time allotted to remedy the problem exceeds human limits (as is often the case during nap-of-the-earth flight). Nevertheless, even when favorable visual cues or an abundance of time is available, there are instances when an individual may simply not possess the necessary aptitude, physical ability, or proficiency to operate safely.

Substandard practices of the operator: Often times, the substandard practices of aircrew will lead to the conditions and unsafe acts described above. For instance, the failure to ensure that all members of the crew are acting in a coordinated manner can lead to confusion (adverse mental state) and poor decisions in the cockpit. *Crew resource mismanagement,* as it is referred to here, includes the failures of both inter- and intra-cockpit communication, as well as communication with ATC and other ground personnel. This category also includes those instances when crewmembers do not work together as a team, or when individuals directly responsible for the conduct of operations fail to coordinate activities before, during and after a flight.

Equally important however, individuals must ensure that they are adequately prepared individually for flight. Consequently, the category of *personal readiness* was created to account for those instances when rules such as disregarding crew rest requirements, violating alcohol restrictions, self-medicating, are not adhered to. However, even behaviors that do not necessarily violate existing rules or regulations (e.g., running 10 mi before piloting an aircraft or poor dietary practices) may reduce the operating capabilities of the individual and are therefore captured here.

Unsafe Supervision

Clearly aircrew are responsible for their actions and as such must be held accountable. However, in many instances they are the unwitting inheritors of latent failures attributable to those who supervise them (12). To account for these latent failures, the overarching category of unsafe supervision was created within which four categories (inadequate supervision, planned inappropriate operations, failed to correct known problems, and supervisory violations) are included.

The first category, *inadequate supervision,* refers to failures within the supervisory chain of command which were a direct result of some supervisory action or inaction. That is, at a minimum, supervisors must provide the opportunity for individuals to succeed. It is expected therefore, that individuals will receive adequate training, professional guidance, oversight, and operational leadership, and that all will be managed appropriately. When this is not the case, aircrew are often

isolated as the risk associated with day-to-day operations invariably will increase.

However, the risk associated with supervisory failures can come in many forms. Occasionally, for example, the operational tempo and/or schedule is planned such that individuals are put at unacceptable risk and ultimately performance is adversely affected. As such, the category of *planned inappropriate operations* was created to account for all aspects of improper or inappropriate crew scheduling and operational planning which may focus on such issues as crew pairing, crew rest, and managing the risk associated with specific missions.

The remaining two categories of unsafe supervision, the *failure to correct known problems* and *supervisory violations*, are similar, yet considered separately, within HFACS. The failure to correct known problems refers to those instances when deficiencies among individuals, equipment, training or other related safety areas are "known" to the supervisor yet are allowed to continue uncorrected. For example, the failure to consistently correct or discipline inappropriate behavior certainly fosters an unsafe atmosphere, but is not considered a violation if no specific rules or regulations were broken.

Supervisory violations, on the other hand, are reserved for those instances when existing rules and regulations are willfully disregarded by supervisors when managing assets. For instance, permitting aircrew to operate an aircraft without current qualifications or license is a flagrant violation that invariably sets the stage for the tragic sequence of events that predictably follow.

Organizational Influences

Fallible decisions of upper-level management can directly affect supervisory practices, as well as the conditions and actions of operators. Unfortunately, these *organizational influences* often go unnoticed or unreported by even the best-intentioned accident investigators.

Traditionally, these latent organizational failures generally revolve around three issues: 1) resource management; 2) organizational climate; and 3) operational processes. The first category, *resource management*, refers to the management, allocation, and maintenance of organizational resources, including human resource management (selection, training, staffing), monetary safety budgets, and equipment design (ergonomic specifications). In general, corporate decisions about how such resources should be managed center around two distinct objectives –the goal of safety and the goal of on-time, cost-effective operations. In times of prosperity, both objectives can be easily balanced and satisfied in full. However, there may also be times of fiscal austerity that demand some give and take between the two. Unfortunately, history tells us that safety is often the loser in such battles as safety and training are often the first to be cut in organizations having financial difficulties.

Organizational climate refers to a broad class of organizational variables that influence worker performance and is defined as the "situationally based consistencies in the organization's treatment of individuals." (6). One telltale sign of an organization's climate is its structure, as reflected in the chain-of-command, delegation of authority and responsibility, communication channels, and formal accountability for actions. Just like in the cockpit, communication and coordination are vital within an organization. However, an organization's policies and culture are also good indicators of its climate. Consequently, when policies are ill-defined, adversarial, or conflicting, or when they are supplanted by unofficial rules and values, confusion abounds, and safety suffers within an organization.

Finally, *operational process* refers to formal processes (operational tempo, time pressures, production quotas, incentive systems, schedules, etc.), procedures (performance standards, objectives, documentation, instructions about procedures, etc.), and oversight within the organization (organizational self-study, risk management, and the establishment and use of safety programs). Poor upper-level management and decisions concerning each of these organizational factors can also have a negative, albeit indirect, affect on operator performance and system safety.

Summary

The HFACS framework bridges the gap between theory and practice by providing safety professionals with a theoretically based tool for identifying and classifying the human causes of aviation accidents. Because the system focuses on both latent and active failures and their interrelationships, it facilitates the identification of the underlying causes of human error. To date, HFACS has been shown to be useful within the context of military aviation, as both a data analysis framework and an accident investigation tool. However, HFACS has yet to be applied systematically to the analysis and investigation of civil aviation accidents. The purpose of the present research project, therefore, was to assess the utility of the HFACS framework as an error analysis and classification tool within the commercial aviation arena.

The specific objectives of this study were three fold. The first objective was to determine whether the HFACS framework, in its current form, would be comprehensive enough to accommodate all of the underlying human causal-factors associated with commercial aviation accidents as contained in the accident databases maintained by the FAA and NTSB. In other words, could the framework capture all the relevant human error data or would a portion of the database be lost because it was unclassifiable. The second objective was to determine whether the process of reclassifying the human causal factors using HFACS was reliable. That is, would different users of the system agree on how causal factors should be coded using the framework. Finally, the third objective was to determine whether reclassifying the data using HFACS yield a benefit beyond what is already known about commercial aviation accident causation. Specifically, would HFACS highlight any heretofore unknown safety issues in need of further intervention research.

METHODS

Data

A comprehensive review of all accidents involving Code of Federal Air Regulations (FAR) Part 121 and 135 Scheduled Air Carriers* between January 1990 and December 1996 was conducted using database records maintained by the NTSB and the FAA. Of particular interest to this study, were those accidents attributable, at least in part, to the aircrew. Consequently, accidents due solely to catastrophic failure, maintenance error and unavoidable weather conditions such as turbulence and wind shear were not included. Furthermore, only those accidents in which the investigation was completed, and the cause of the accident determined, were included in this analysis. There were 119 accidents which met these criteria, including 44 accidents involving FAR Part 121 operators and 75 accidents involving FAR Part 135 operators.

HFACS Classification

The 119 aircrew-related accidents yielded 319 causal factors for further analyses. Each of these NTSB causal factors was subsequently coded independently by both an aviation psychologist and a commercially rated pilot using the HFACS framework. Only those causal factors identified by the NTSB were analyzed. That is, no new causal factors were created during the error-coding process.

RESULTS

HFACS Comprehensiveness

All 319 (100%) of the human causal factors associated with aircrew-related accidents were accommodated using the HFACS framework. Instances of all but two HFACS categories (i.e., organizational climate and personal readiness) were observed as least once in the accident database. Therefore, no new HFACS categories were needed to capture the existing causal factors and no human factors data pertaining to the aircrew was left unclassified during the coding process.

HFACS Reliability

Disagreements among raters were noted during the coding process. When disagreements did occur, they were resolved through discussion until agreement could be reached. These discussions involved coders describing their rationale for the way they had classified a particular causal factor and justifying their decision based on the details contained in the narrative report of the accident. Overall, coders initially agreed on approximately 76% of the causal factor reclassifications and were able to reach consensus on the recoding of all of the factors. To further examine the reliability of the HFACS system, Cohen's *Kappa* was calculated using coders' overall agreement rate. *Kappa* is a more stringent index of inter-rater reliability in that it accounts for the probability of coders agreeing simply by chance on the classification of any given causal factor. The obtained *Kappa* value was 0.71, which generally reflects a "good" level of agreement according to criteria described by Fleiss (2).

TABLE I. PERCENTAGE OF ACCIDENTS ASSOCIATED WITH EACH HFACS CATEGORY.

HFACS Category	FAR Part 121	FAR Part 135	Total
Organizational Influences			
Resource Management	4.5 (2)	1.3 (1)	2.5 (3)
Organizational Climate	0.0 (0)	0.0 (0)	0.0 (0)
Organizational Process	15.9 (7)	4.0 (3)	8.4 (10)
Unsafe Supervision			
Inadequate Supervision	2.3 (1)	6.7 (5)	5.0 (6)
Planned Inappropriate Operations	0.0 (0)	1.3 (1)	0.8 (1)
Failed to Correct Known Problem	0.0 (0)	2.7 (2)	1.7 (2)
Supervisory Violations	0.0 (0)	2.7 (2)	1.7 (2)
Preconditions of Unsafe Acts			
Adverse Mental States	13.6 (6)	13.3 (10)	13.4 (16)
Adverse Physiological Sates	4.5 (2)	0.0 (0)	1.7 (2)
Physical/mental Limitations	2.3 (1)	16.0 (12)	10.9 (13)
Crew-resource Mismanagement	40.9 (18)	22.7 (17)	29.4 (35)
Personal Readiness	0.0 (0)	0.0 (0)	0.0 (0)
Unsafe Acts			
Skill-based Errors	63.6 (28)	58.7 (44)	60.5 (72)
Decision Errors	25.0 (11)	30.7 (23)	28.6 (34)
Perceptual Errors	20.5 (9)	10.7 (8)	14.3 (17)
Violations	25.0 (11)	28.0 (21)	26.9 (32)

Note. Numbers in table are percentages of accidents that involved at least one instance of an HFACS category. Numbers in parentheses indicate accident frequencies. Because more than one causal factor is generally associated with each accident, the percentages in the table will not equal 100%.

HFACS Analyses

Unsafe acts: **Table I** presents percentages of FAR Part 121 and 135 aircrew-related accidents associated with each of the HFACS categories. An examination of the table reveals that at the unsafe acts level, skill-based errors were associated with the largest percentage of accidents. Approximately 60% of all aircrew-related accidents were associated with at least one skill-based error. This percentage was relatively similar for FAR Part 121 carriers (63.6%) and FAR Part 135 carriers (58.7%). **Fig. 4**, panel A, illustrates that the proportion of accidents associated with skill-based errors has remained relatively unchanged over the 7-yr period examined in the study. Notably however, the lowest proportion of accidents associated with skill-based errors was observed in the last 2 yr of the study (1995 and 1996).

Among the remaining categories of unsafe acts, accidents associated with decision errors constituted the next highest proportion (i.e., roughly 29% of the accidents examined, Table I). Again, this percentage was roughly equal across both FAR Part 121 (25.0%) and Part 135 (30.7%) accidents. With the exception of 1994 in

*FAR Part 121 Schedule Carriers refers to major commercial airlines whose operations are governed by the Federal Aviation Regulations (FAR), Part (i.e., section) 121. FAR Part 135 schedule carriers refers to smaller commuter airlines or air services whose operations are governed by the Federal Aviation Regulations, Part 135.

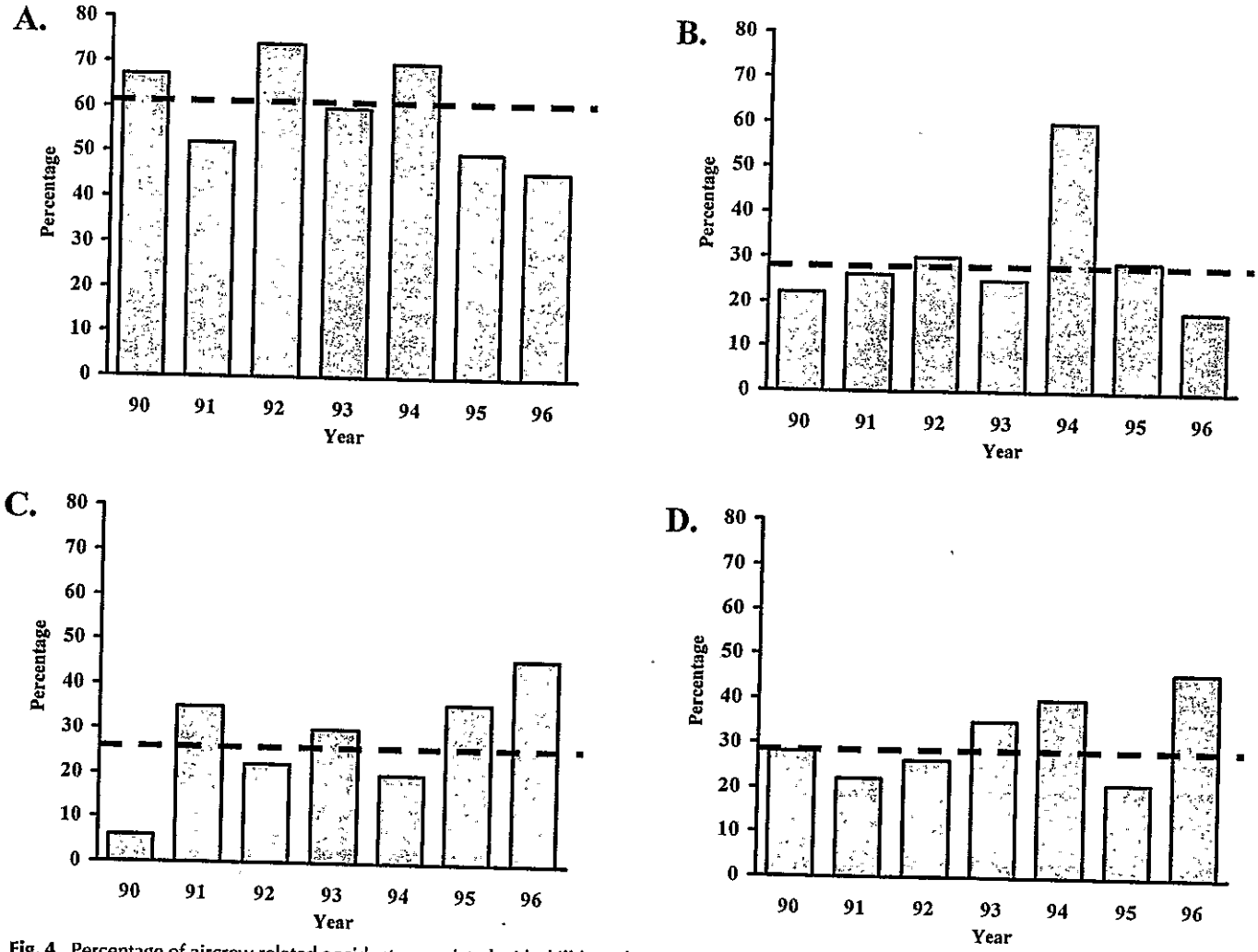

Fig. 4. Percentage of aircrew related accidents associated with skill-based errors (Panel A), decision errors (Panel B), violations (Panel C), and CRM failures (Panel D) across calendar years. Lines represent 7-yr averages.

which the percentage of aircrew-related accidents associated with decision errors reached a high of 60%, the proportion of accidents associated with decision errors remained relatively constant across the years of the study (Fig. 4, panel B).

Similar to accidents associated with decision errors, those attributable at least in part to violations of rules and regulations were associated with 26.9% of the accidents examined. Again, no appreciable difference was evident when comparing the relative percentages across FAR Part 121 (25.0%) and 135 (28.0%). However, an examination of Fig. 4, panel C, reveals that the relative proportion of accidents associated with violations increased appreciably from a low of 6% in 1990 to a high of 46% in 1996.

Finally, the proportion of accidents associated with perceptual errors was relatively low. In fact, only 17 of the 119 accidents (14.3%) involved some form of perceptual error. While it appeared that the relative proportion of Part 121 accidents associated with perceptual errors was higher than Part 135 accidents, the low number of occurrences precluded any meaningful comparisons across either the type of operation or calendar year.

Preconditions for unsafe acts: Within the preconditions level, CRM failures were associated with the largest percentage of accidents. Approximately 29.4% of all aircrew-related accidents were associated with at least one CRM failure. A relatively larger percentage of FAR Part 121 aircrew-accidents involved CRM failures (40.9%) than did FAR Part 135 aircrew-related accidents (22.7%). However, the percentage of accidents associated with CRM failures remained relatively constant over the 7-yr period for both FAR Part 121 and 135 carriers (Fig. 4, panel D).

The next largest percentage of accidents were those associated with adverse mental states (13.4%), followed by physical/mental limitations (10.9%) and adverse physiological states (1.7%). There were no accidents associated with personal readiness issues. The percentage of accidents associated with physical/mental limitation was slightly higher for FAR Part 135 carriers (16%) compared with FAR Part 121 carriers (2.3%), but accidents associated with adverse mental or adverse physiological states were relatively equal across carriers. Again, however, the low number of occurrences in each of these accident categories precluded any meaningful comparisons across calendar year.

Supervisory and Organizational Factors

Very few of the NTSB reports that implicated the aircrew as contributing to an accident also cited some form of supervisory or organizational failure (see Table I). Indeed, only 16% of all aircrew-related accidents involved some form of either supervisory or organizational involvement. Overall however, a larger proportion of aircrew-related accidents involving FAR Part 135 carriers involved supervisory failures (9.3%) than did those accidents involving FAR Part 121 carriers (2.3%). In contrast, a larger proportion of aircrew-related accidents involving FAR Part 121 carriers involved organizational factors (20.5%) than did those accidents involving FAR Part 135 carriers (4.0%).

DISCUSSION

HFACS Comprehensiveness

The HFACS framework was found to accommodate all 319 causal factors associated with the 119 accidents involving FAR Part 121 and 135 scheduled carriers across the 7-yr period examined. This finding suggests that the error categories within HFACS that were originally developed for use in the military, are applicable within commercial aviation as well. Still, some of the error-factors within the HFACS framework were never observed in the commercial aviation accident database. For example, no instances of such factors as organizational climate or personal readiness were observed. In fact, very few instances of supervisory factors were evident at all in the data.

One explanation for the scarcity of such factors could be that contrary to Reason's model of latent and active failures on which HFACS is based, such supervisory and organizational factors simply do not play as large of a role in the etiology of commercial aviation accidents as once expected. Consequently, the HFACS framework may need to be pared down or simplified for use with commercial aviation. Another explanation, however, is that these factors do contribute to most accidents, yet they are rarely identified using existing accident investigation processes. Nevertheless, the result of this study indicate that the HFACS framework was able to capture all existing causal factors and no new error-categories or aircrew cause-factors were needed to analyze the commercial accident data.

HFACS Reliability

The HFACS system was found to produce an acceptable level of agreement among the investigators who participated in this study. Furthermore, even after this level of agreement between investigators was corrected for chance, the obtained reliability index was considered "good" by conventional standards. Still, this reliability index was somewhat lower than those observed in studies using military aviation accidents, which in some instances have resulted in nearly complete agreement among investigators (17).

One possible explanation for this discrepancy is the difference in both the type and amount of information available to investigators across these studies. Unlike the present study, previous analysts using HFACS to analyze military accident data often had access to privileged and highly detailed information about the accidents, which presumably allowed for a better understanding of the underlying causal factors and hence produced higher levels of reliabilities. Another possibility is that the definitions and examples currently used to describe HFACS are too closely tied to military aviation and are, therefore, somewhat ambiguous to those within a commercial setting. Indeed, the reliability of the HFACS framework has been shown to improve within the commercial aviation domain when efforts are taken to provide examples and checklists that are more compatible with civil aviation accidents (24).

HFACS Analysis

Given the large number of accident causal factors contained in the NTSB database, each accident appeared, at least on the surface, to be relatively unique. As such, commonalities or trends in specific error forms across accidents were not readily evident in the data. Still the recoding of the data using HFACS did allow for similar error-forms and causal factors across accidents to be identified and the major human causes of accidents to be discovered.

Specifically, the HFACS analysis revealed that the highest percentage of all aircrew-related accidents were associated with skill-based errors. Furthermore, this proportion was lowest during the last 2 yr of this study, suggesting that the percentage of accidents associated with skill-based errors may be on the decline. To some, the finding that skill-based errors were frequently observed among the commercial aviation accidents examined is not surprising given the dynamic nature and complexity of piloting commercial aircraft, particularly in the increasingly congested U.S. airspace. The question remains, however, as to the driving force behind the possible reduction in such errors. Explanations could include improved aircrew training practices or perhaps better selection procedures. Another possibility might be the recent transition within the regional commuter industry from turboprop to jet aircraft. Such aircraft are generally more reliable and contain advanced automation to help off-load the attentional and memory demands placed on pilots during flight.

Unfortunately, the industry-wide intervention programs and other changes that were made during the 1990's were neither systematically applied nor targeted at preventing specific error types, such as skill-based errors. Consequently, it is impossible to determine whether all or only a few of these efforts are responsible for the apparent decline in skill-based errors. Nevertheless, given that an error analysis has now been conducted on the accident data, future intervention programs can be strategically targeted at reducing skill-based errors. Furthermore, the effectiveness of such efforts can be objectively evaluated so that efforts can be either reinforced or revamped to improve safety. Additionally, intervention ideas can now also be shared across organizations that have performed similar HFACS analyses. One example is the U.S. Navy and

Marine Corps that has recently initiated a systematic intervention program for addressing their growing problem with accidents associated with skill-based errors in the fleet (19). As a result, lessons learned in the military can now be communicated and shared with the commercial aviation industry, and vice versa.

The observation that both CRM failures and decision errors are associated with a large percentage of aircrew-related accidents is also not surprising given that these findings parallel the results of similar HFACS and human error analyses of both military and civil aviation accidents (9,23). What is surprising, or at least somewhat disconcerting, is the observation that the percentage of aircrew-related accidents associated with both CRM and decision errors has remained relatively stable. Indeed, both the FAA and aviation industry have invested a great deal of resources into intervention strategies specifically targeted at improving CRM and aeronautical decision making (ADM), with apparently little overall effect.

The modest impact that CRM and ADM programs have had on reducing accidents may be due to a variety of factors, including the general lack of a systematic analyses of accidents associated with these problems. Consequently, most CRM and ADM training programs have used single case studies to educate aircrew, rather then focus on the fundamental causes of these problems in the cockpit using a systematic analysis of the accident data. Another possible explanation for the general lack of CRM and ADM effectiveness is that most training programs involve classroom exercises that are not followed up by simulator training that requires CRM and ADM principles to be applied. More recent programs, such as the Advanced Qualification Program (AQP), have recently been developed to take this next step of integrating ADM and CRM principles into the cockpit. Given that the current HFACS analyses has identified the accidents associated with these problems, at least across a 7-yr period, a more fine-grained analyses can be conducted to identify the specific problems areas in need of training. Furthermore, the effectiveness of the AQP program and other ADM training in reducing aircrew accidents associated with CRM failures and decision errors can be systematically tracked and evaluated.

The percentage of aircrew related accidents associated with violations (e.g., not following federal regulations or a company's standard-operating-procedures) exhibited a slight increase across the years examined in this study. Some authors (e.g., 4) have suggested that violations, such as taking short-cuts in procedures or breaking rules, are often induced by situational factors that reinforce unsafe acts while punishing safe actions. Not performing a thorough preflight inspection due to the pressure to achieve an on-time departure would be one example. However, according to Reason's (12) model of active and latent failures, such violation-inducing situations are often set up by supervisory and management policies and practices.

Such theories suggest that the best strategy for reducing violations by aircrew is to enforce the rules and to hold both the aircrew and their supervisors/organizations accountable. Indeed, this strategy has been effective with the Navy and Marine Corps in reducing aviation mishaps associate with violations (21). Still, as mentioned earlier, very few of the commercial accident reports examined in this study cited supervisory or organizational factors as accident causes, suggesting that more often than not, aircrew were the only ones responsible for the violations. Again, more thorough accident investigations may need to be performed to identify the possible supervisory and organizational issues associated with these events.

Although FAR Part 135 scheduled carriers had fewer annual flight hours during the years covered in this study (7), the overall number of accidents associated with most error types was generally higher for FAR Part 135 scheduled carriers compared with FAR Part 121 scheduled carriers. This finding is likely due, at least in part, to the fact that most pilots flying aircraft operating under FAR Part 135 are younger and much less experienced. Furthermore, such pilots are often flying less sophisticated and reliable aircraft into areas that are less likely to be controlled by ATC. As a result, they may find themselves more often in situations that exceed their training or abilities. Such a conclusion is supported by the findings presented here, since a larger percentage of FAR Part 135 aircrew-related accidents were associated with the physical/mental limitations of the pilot. However, a smaller percentage FAR Part 135 aircrew accidents were associated with CRM failures, which may be due to the fact that pilots of FAR Part 135 aircraft are generally younger and have thus been exposed to CRM concepts since the beginning of their flight training.

These differences between FAR Part 121 and 135 schedule carriers may be less evident in future aviation accident data since the Federal Regulations were changed in 1997. Such changes require smaller FAR Part 135 carriers operating aircraft that carrier 10 or more passengers to now operate under more stringent FAR Part 121 rules. Thus, the historical distinction in the database between FAR Part 135 and 121 operators has become somewhat blurred in the years extending beyond the current analysis. Future human-error analyses and comparisons across these different types of commercial operations will therefore need to consider these changes.

SUMMARY AND CONCLUSIONS

This investigation demonstrates that the HFACS framework, originally developed for and proven in the military, can be used to reliably identify the underlying human factors problems associated with commercial aviation accidents. Furthermore, the results of this study highlight critical areas of human factors in need of further safety research and provide the foundation on which to build a larger civil aviation safety program. Ultimately, data analyses such as that presented here will provide valuable insight aimed at the reduction of aviation accidents through data-driven investment strategies and objective evaluation of intervention programs. The HFACS framework may also prove useful as a tool for guiding future accident investigations in

the field and developing better accident databases, both of which would improve the overall quality and accessibility of human factors accident data.

It should be noted however, that HFACS is not a standalone accident investigation system. Such critical information as the sequencing of events, the varying importance of different factors, and the level of certainty of investigators regarding specific factors are not part of HFACS. Rather, HFACS is a framework around which a comprehensive accident investigation system can be built. Given its theoretical roots in Reason's model of latent and active failures, the HFACS categories imply relationships between variables, both in terms of their temporal and causal connections. As such, HFACS provides both a theoretical and practical foundation for developing and integrating the multiple and diverse components that constitute an effective accident investigation and prevention program.

Still, the HFACS framework is not the only possible tool on which such programs might be developed. Indeed, there often appear to be as many human error frameworks as there are those interested in the topic (14). Indeed, as the need for better *applied* human error analysis methods has become more apparent, an increasing number of researchers have proposed other comprehensive frameworks similar to HFACS (e.g., 8). Nevertheless, HFACS is, to date, the only system that has been developed to meet a specific set of design criteria, including comprehensiveness, reliability, diagnosticity, and usability, all of which have contributed to the framework's validity as an accident analysis tool (20). Furthermore, HFACS has been shown to have utility as an error-analysis tool in other aviation-related domains such as ATC (HFACS-ATC; 10) and aviation maintenance (HFACS-ME; 13), and is currently being evaluated within other complex systems such as medicine (currently referred to as HFACS-M.D.). Finally, it is important to remember that neither HFACS, nor any other error-analysis tool, can "fix" the problems once they have been identified. Such fixes can only be derived by those organizations, practitioners and human factors professionals who are dedicated to improving aviation safety.

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