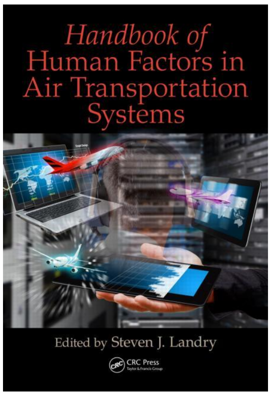

Handbook of Human Factors in Air Transportation Systems

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Accident Investigation

Publication details
https://test.routledgehandbooks.com/doi/10.1201/9781315116549-6
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Published online on: 15 Nov 2017

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INTRODUCTION

Accident investigation is a sense-making activity, a way of understanding events that frighten us, and, hopefully, finding ways to reduce the risk of those events in the future. It is a multidisciplinary field that requires collaboration among professionals of many backgrounds, including flight operations, air traffic control, maintenance, and cabin safety. The participation of these varied specialties is needed to understand the complexity of aviation work and to develop a sufficiently detailed record on which to base an analysis. Due to this disciplinary diversity, accident investigation is also a team activity, and the National Transportation Safety Board (NTSB) has developed an organizational framework based on these technical specialties to impose order on the process.

Investigative work is divided up by working groups led by an investigator from each technical specialty. Operations investigators examine flight deck operations and work in the cockpit. Survival factors investigators examine cabin operations and the work of flight attendants and airport rescue personnel. Air traffic control investigators examine air traffic operations in towers and centers. Maintenance investigators examine work in the maintenance hangar. Engineering investigators examine the design and functioning of aircraft structures, systems, and powerplants. The role of the human factors investigator is uniquely broad. Human factors investigators are charged with examining issues that may span these domains. This boundary crossing makes the work of the human factors investigator unique and sometimes leads to confusion about the investigators' role relative to the role of other investigative team members.

The role of the human factors investigator is spelled out in the International Civil Aviation Organization's (ICAO's) *Manual of Aircraft Accident and Incident Investigation* (International Civil Aviation Organization, 2014). According to this manual, the objectives of human factors investigation are to

- Determine how breakdowns in human performance may have caused or contributed to an occurrence.
- Identify safety hazards related to limitations in human performance.
- Identify ways to eliminate or reduce the consequences of faulty human actions or decisions.

Interpretation of these objectives depends on one's knowledge of human factors and one's preferred theoretical perspective on the nature of human error.

SOME HISTORY

Flying was risky in the early days of aviation. About half of U.S. Air Mail pilots died in crashes during the service's first two years of operation (U.S. Centennial of Flight Commission, 2017), underscoring the riskiness of early flight. Aircraft accidents of the 1920s were attributed to a range of factors, including defective equipment, faulty maintenance, and of course, human causes (Wilson, 1949). In 1926, the U.S. Congress established a Bureau of Air Commerce to establish and enforce new safety rules. The Bureau's Aeronautics Branch was responsible for investigating crashes. However, a series of high profile accidents led to the establishment of a new three-member Air Safety Board. In 1940, the Civil Aeronautics Board (CAB) was formed, and it assumed the functions of both regulating safety and investigating accidents.

By this time, airlines were ferrying passengers around the globe in aircraft with as many as 50 seats. Airline accidents were attributed to a variety of factors including structural failures, engine failures, terrain, weather, darkness, and human failures including *poor technique, defective judgment, carelessness* (Wilson, 1949, p. 443). During and after World War II, manufacturers adopted new technologies, including the gyropilot, turbo-supercharger control, propeller-feathering mechanism, and control surface compensator. Such technologies were seen as encroaching on the responsibilities of pilots, but the industry regarded the tools as *instrumental in eliminating human error*. After the war, airlines campaigned for accelerated deployment of ground and airborne navigation equipment, radar, and high-intensity approach lighting. Fatal accident rates began to drop (Figure 6.1).

A series of midair collisions in the 1950s, including the 1956 collision of a United Airlines DC-7 and a Trans World Airlines L-1049 over the Grand Canyon, spurred development of a more robust air traffic control system, and, in 1958, Congress established a new Federal Aviation Agency (later renamed the Federal Aviation Administration or FAA). The FAA took charge of safety regulation and enforcement, whereas the CAB retained responsibility for regulating air commerce and investigating accidents. The march of aviation technology continued. Manufacturers introduced the first jet airliner, the DeHavilland Comet. The Comet was plagued

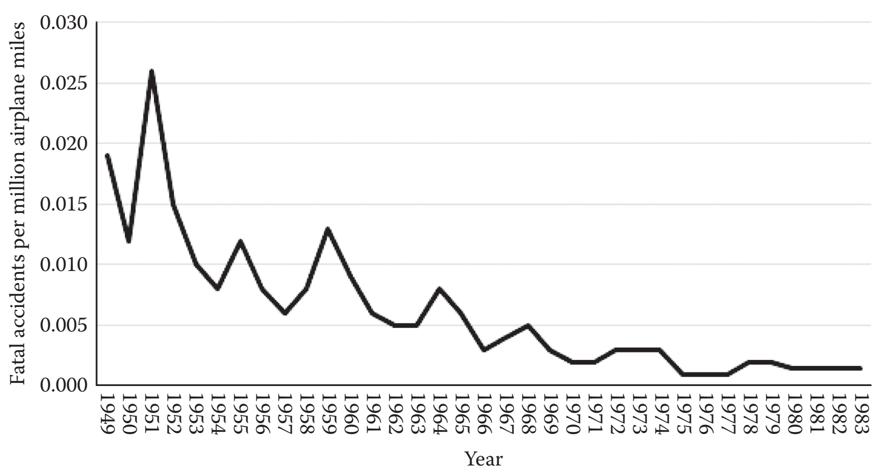

FIGURE 6.1 Fatal accidents per million airplane miles flown, scheduled operations, 1949–1983. (From Compilation of CAB and NTSB statistics. With Permission.)

with safety issues, but it heralded a new era in commercial aviation. The fatal accident rate for U.S. scheduled airlines continued its decline.

The 1960s saw a proliferation of narrow-body jet airliners. These airplanes carried more than 100 passengers, including the Douglas DC-8, DC-9, and DC-10, and the Boeing B-727 and B-737. These aircraft were equipped with more reliable engines and could fly at higher altitudes. This reduced the risk of engine failure and allowed flights to better avoid hazardous weather. The fatal accident rate reached an impressive new low of around 0.003 fatal accidents per million airplane miles. In 1966, a multimodal NTSB was established within the new U.S. Department of Transportation (DOT), and the NTSB was given responsibility for investigating civil aircraft accidents. Originally, part of the DOT, NTSB was made independent in 1975 to enhance its ability to report objectively on the adequacy of DOT regulation and oversight.

The 1970s saw the introduction of wide-body jetliners carrying more than 200 passengers, such as the Boeing B-747, DC-10, Lockheed L-1011, and Airbus A-300. Now, an airline crash truly raised the prospect of mass fatalities, and this unfortunately did happen a few times in that decade. The worst of these accidents occurred in 1977 in Tenerife, Spanish Canary Islands, when two B-747 airplanes collided on a foggy runway (Comisión de Investigación de Accidentes e Incidentes de Aviación Civil, 1978). The decline in the fatal accident rate that had been occurring over the previous decades began to stall, and the aviation safety community found itself searching for answers. The majority of major aircraft accidents were being attributed to pilot error, and this prompted increased interest in human factors.

GRAPPLING WITH HUMAN FACTORS

Aviation safety professionals have long recognized the need to look beyond pilot error to understand aviation safety issues. As McFarland (1946) stated

> Only in isolated cases is it possible to apportion the causes of the accident to specific faults rather than to an accumulation of contributing factors. Many accidents that have been attributed to pilot error may have resulted from excessive demands on the air crews. While training and selection procedures may be improved, it is unlikely that human limitations in operating aircraft can be appreciably altered. The aeronautical engineer, however may be able to simplify the duties of the pilot and thus reduce the likelihood of error. (p.561)

A human factors branch was first established at the CAB in 1959, but its scope was fairly limited. It was primarily concerned with identifying injury mechanisms and evaluating the crashworthiness of vehicles. In the 1960s, the division's responsibilities were expanded to include investigation of operators' medical, psychological, and physical fitness for duty (Doyle, 1968). By the 1970s, the division's efforts had expanded to include human performance, which was essentially an activity aimed at identifying reasons for unexpected deviations from desired crew performance. With this addition, the efforts of the branch's investigators were divided into three areas:

- Medical and crush injury factors
- Survival and other postcrash factors and
- Human performance factors

The Board approached the investigation of human factors as part of an *investigative triad* Miller (1971). This was a decompositional approach in which investigative activities were divided into three areas: *man, machine,* and *medium*. *Man* stood for the human element, *machine* for the aircraft, and *medium* for operational aspects. Investigative divisions were organized accordingly. They included an aircraft branch, a human factors branch, and an operational factors branch. The aircraft branch examined mechanical aspects of the aircraft. The human factors branch examined physiology, psychology, human engineering, and survivability. The operations branch explored *operational aspects*. NTSB managers recognized a significant amount of overlap between human factors and operational aspects, acknowledging that the division of labor on topics like flightcrew training was somewhat arbitrary (Miller, 1971).

Miller (1971), who directed the NTSB's Bureau of Aviation Safety in the early 1970s, considered investigation of human factors *the greatest single technological challenge* for investigators. He urged exploration of pilot skill, judgment, and personality and felt that the solutions to problems in these areas would involve education, enforcement, and engineering. He also saw the need for an investigative specialty that could tie together the disparate factors identified in an investigation, including organizational aspects. He felt this specialty should be systems safety, a new discipline in which he was a pioneering influence (Miller, 1954) that focused on "the integration of skills and resources, specifically organized to achieve accident prevention over the life cycle of an air vehicle system" (Miller, 1965). According to Miller (1971), the NTSB explored the hiring of systems safety specialists; however, systems safety never became a major area of specialization at the NTSB.

Danaher (1971) was chief of the NTSB's human factors branch in the 1970s. He observed that NTSB findings were too often, "objective summaries of what happened rather than statements of the true underlying cause of the accident." He felt that addressing these underlying causes was important and that it would require greater attention to human factors; however, he did not describe how the investigation of such factors should be carried out. In a 1974 paper, the National Air Transportation Associations (Macy, 1974) criticized the NTSB's existing approach to investigating human factors that included probing a pilot's mood, feelings, and habits. The organization argued that investigators lacked adequate research describing the factors affecting pilots' performance of operational tasks, and it advocated for the study of pilot behavior in realistic operational contexts.

Shortly thereafter, a group of NASA researchers began research examining crew performance, and they issued some recommendations for studying crew behavior and investigating human factors in aircraft accidents and incidents (Barnhart et al., 1975; Cooper et al., 1980). The NASA group recommended the creation of a timeline of significant behavioral events, the making of inferences about how these events affected the broader event sequence, which they called a function analysis. They also urged the application of information processing models to gain deeper insight into the context of flightcrew errors. The approach reflected trends in psychology at the time, which emphasized the study of cognition and compared the functioning of the brain with a computer.

Schleede (1979), a senior NTSB air safety investigator, tried this approach in his own investigations and found it helpful. He encouraged other investigators to use of it but pointed out that doing so would require a change of mindset. Schleede observed that accident investigators, many of whom were engineers, were most comfortable applying deductive reasoning to their investigations. He argued that the use of deductive reasoning was not possible when analyzing human performance as it was when analyzing mechanical failures because some of the factors influencing human performance (such as cognition) were not directly observable, and because the influence of various factors on behavior was probabilistic. The shift to a more inductive approach was essential, he reasoned, if the air safety community was to make significant progress addressing safety issues related to pilot error.

BUILDING A HUMAN PERFORMANCE INVESTIGATION CAPABILITY AT THE NTSB

In 1977, the NTSB hired its first engineering psychologist to investigate human performance issues. This investigator, Alan Diehl, participated in at least two significant investigations during his time at the board. The first was an accident involving United Airlines Flight 173, which crashed after running out of fuel in Portland, Oregon (National Transportation Safety Board, 1979). As Kayten (1993) wrote, this accident occurred soon after NASA's safety researchers had developed a new vocabulary and framework for analyzing crew performance called cockpit resource management (CRM). Diehl identified CRM-related deficiencies in the crew's performance and drafted the Board's first recommendation urging the provision of CRM training to airline pilots emphasizing "the merits of participative management for captains and assertiveness training for other cockpit crewmembers." Subsequently, Diehl participated in the investigation of a commuter airline accident in Rockland, Maine. He also identified CRM issues in that accident, and he uncovered management pressures encouraging risky pilot decisions (National Transportation Safety Board, 1980).

These investigations, and sustained industry pressure to do a better job, addressing the factors underlying pilot error prompted the NTSB to develop a systematic framework for investigating human performance. This frame work was created following a review of investigative protocols used by various organizations, including the U.S. Air Force, Army, and Navy, and by British, Canadian, and the Air Line Pilots Association (National Transportation Safety Board, Unpublished) by the human factors branch. After reviewing these models, the branch evaluated the utility of the various models for discovering human performance issues that had been documented in recent accidents investigated by the NTSB (Walhout, 1981). The resulting framework included six focus areas: behavioral, medical, operational, task, equipment, and environmental factors (Figure 6.2).

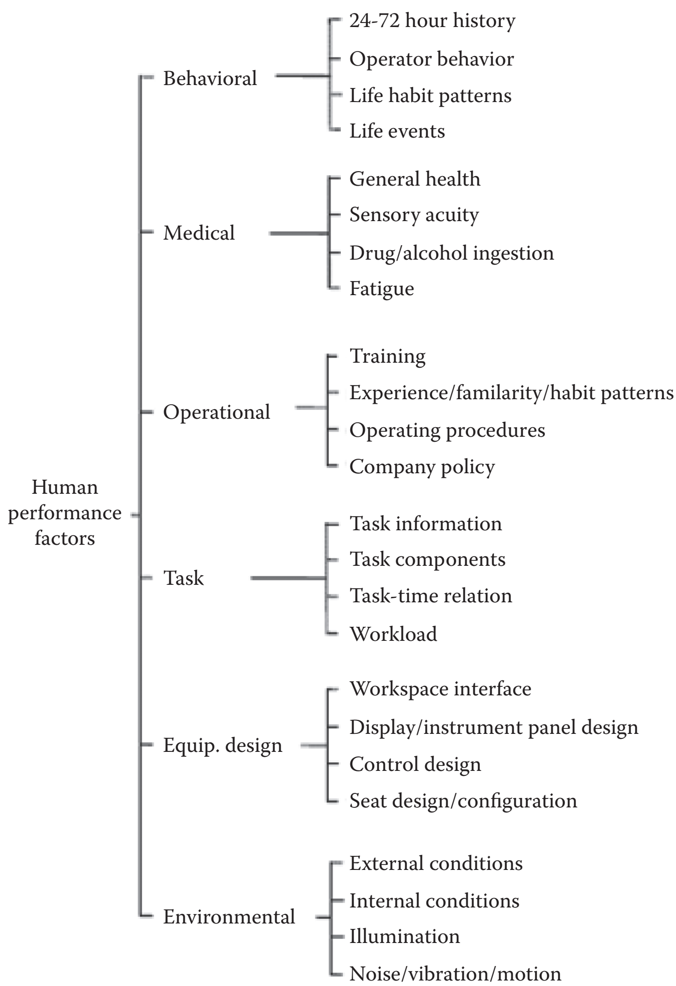

FIGURE 6.2 NTSB human performance investigation model. (From Walhout, G., *ISASI Forum*, 14, 21–22, 1981. With Permission.)

The model did not include a separate category for organization factors, which is surprising, given the success of the Rockland, Maine, investigation, which was touted as a significant accomplishment (Walhout, 1981). The lack of a separate focus area for organizational factors probably reflects the absence at that time of a comprehensive theoretical model addressing the role of organizational factors in accident development.

The human factors branch tested its new human performance model during the investigation of a 1981 air taxi accident near Spokane, Washington (National Transportation Safety Board, 1981). This first formal human performance investigation group was led by an engineering psychologist named Janis Stoklosa, who had filled the position left vacant by Alan Diehl. The group consisted of investigators with a variety of backgrounds. In addition to engineering psychology, medicine and flight operations specialists were included. By using the new human performance investigation model as a guide, this group identified shortcomings in the design of the approach charts and navigation equipment (Stoklosa, 1983). The approach the crew was cleared to conduct required them to tune in two consecutive distance measuring equipment (DME) stations. The crew tuned in the first but not the second DME station, causing them to descend prematurely. Stoklosa and colleagues linked this error to the DME, which could utilize a DME station other than the one specified in its display window if a certain button was pressed.

Walhout (1981) reported that the first formal human performance investigative group encountered difficulty gaining acceptance from other NTSB investigators. Few understood the group's purpose or role. This prompted "an intense educational effort … concerning the purpose of this new investigative technique." Unpublished NTSB training materials dated the following year explain, "In response to the directions of the Office of the Managing Director, has developed a program to investigate the human performance issues in accidents in order to better define the 'why' of accident causes. This program is multi-modal; it has far-reaching potential in accident prevention through the identification of the often complex interrelationships of factors which can affect a person's ability to perform his or her duties." The materials went on to explain that the NTSB's human performance approach offered a "systematic and standardized method to gather, analyze and integrate the medical, operational, environmental, vehicle design, and psycho-physiological factors obtained during accident investigation" (National Transportation Safety Board, 1982, p. 1).

The new human performance model was also used during the investigation of an accident involving Air Florida Flight 90 that crashed during takeoff from Washington National Airport (National Transportation Safety Board, 1982). When exploring the *behavior* element, investigators noted that the first officer in this accident had noticed something wrong with thrust during the takeoff roll and they concluded that he was insufficiently assertive, and the captain was insufficiently receptive to his comments (Stoklosa, 1983). As a result, the NTSB reiterated the recommendation from the Portland accident that urged CRM training. Stoklosa also described the use of a functional flow chart method when examining task-related factors. Consequently of this method, the Board concluded that time pressure likely played a role in the crew's difficulty recognizing and diagnosing the problem with the thrust. Consequently, the agency recommended the installation of runway distance markers at certain airports to help crews evaluate takeoff performance and described the potential benefit of an automated takeoff performance monitoring system.

In 1983, NTSB split the human factors branch into two and created a new, stand-alone human performance division (another new division was created to investigate survival factors). The agency cited three recent investigations when justifying the need for the new division (Kayten, 1993): Allegheny Airlines Flight 485 (National Transportation Safety Board, 1972); Eastern Airlines Flight 401 (National Transportation Safety Board, 1973); and Air Florida Flight 90 (National Transportation Safety Board, 1982). The new human performance division employed six investigators and supported NTSB investigations in all modes of transportation. Ron Schleede, the first chief of the NTSB human performance division, concentrated the division's activities on direct support of investigations of significant interest, educating other (still skeptical) NTSB investigators about the "significance of human performance factors in all accident investigations," and cataloguing human performance data to support future aggregate analyses (Bradley, 1984).

The late 1980s was a very busy period for the new division. Major aircraft accidents happened somewhat frequently, and the division provided direct support in the following cases:

- The 1985 crash of a Delta Lockheed L-1011 that encountered wind shear on approach to Dallas Fort Worth International Airport (National Transportation Safety Board, 1986)
- The 1985 stall and crash of a Galaxy Airlines Lockheed L-188 shortly after takeoff from Reno, Nevada (National Transportation Safety Board, 1986)
- The 1986 midair collision and crash of an Aeronaves de Mexico DC-9 and a general aviation airplane near Cerritos, California (National Transportation Safety Board, 1987)
- The 1987 loss of control and crash of a Continental Airlines DC-9 on takeoff from Denver, Colorado (National Transportation Safety Board, 1988)
- The 1987 crash of a Northwest Airlines MD-82 during takeoff from Detroit Metropolitan Airport (National Transportation Safety Board, 1988)
- The 1988 crash of a Delta Airlines crash Boeing B-727 during an attempted takeoff at Dallas, Texas (National Transportation Safety Board, 1989)
- The 1989 crash of a United Airlines DC-10 in Sioux City, Iowa after an uncontained engine failure (National Transportation Safety Board, 1990)

Human performance issues explored in these investigations included pilot decision-making, procedure design, training, and pilot control (National Transportation Safety Board, 1986); procedural compliance, stress, workload, and training (National Transportation Safety Board, 1986); visual performance and attention (National Transportation Safety Board, 1987); preemployment screening and crew pairing practices (National Transportation Safety Board, 1988); checklist design and procedural compliance (National Transportation Safety Board, 1988) (National Transportation Safety Board, 1989); and maintenance inspection and quality control (National Transportation Safety Board, 1990). Investigator training was spotty. One former investigator was sent out on a major accident before receiving any formal training in the role (Brenner, personal communication, 2017).

One particularly noteworthy accident in the 1980s was the crash of United Airlines Flight 232 (National Transportation Safety Board, 1990). After experiencing a catastrophic engine failure that damaged the airplane's major flight control systems, the crew improvised a control strategy using differential thrust and managed a partially controlled impact that saved the lives of many passengers. NTSB concluded that the crew's performance, which involved efficient distribution of communication and maximum utilization of a fourth crewmember (Predmore, 1991), was "highly commendable and greatly exceeded reasonable expectations." Across the airline industry, this was taken as prime evidence of "the value of cockpit resource management training" which had been provided at some airlines for nearly a decade. During these investigations, human performance investigators supported the development of numerous recommendations. Some of these advocated for the continued development of CRM training programs. Others addressed different aspects of training, and some addressed the design of standard operating procedures and the design and reliability of certain equipment, including collision avoidance and configuration warning devices.

In 1990, the NTSB's human performance function was again reorganized. Half of its investigators were assigned to a new aviation human performance division, others to a new sister division in the NTSB Office of Surface Transportation. Thereafter, the agency's aviation human performance investigators focused their efforts on the unique aspects of this complex mode of transportation. The new human performance division employed three investigators, two of whom had PhDs and aviation technical experience (Brenner, personal communication, 2017). This staffing level has been maintained, more or less, to the present day. Beginning in the early 1990s, however, all aviation human performance investigators have been equipped with PhDs in psychology and at least some aviation training and experience (usually a private pilot's license). After plateauing in the

1980s, airline accident rates increased and the frequency of accidents roughly doubled in the 1990s (National Transportation Safety Board, 2002b). The NTSB's aviation human performance investigators remained busy supporting many additional major investigations. Investigations supported during the early 1990s included the following:

- The 1990 runway collision between a Northwest Airlines DC-9 and a Northwest Airlines B-727 in Detroit Metropolitan Airport (National Transportation Safety Board, 1991)
- The 1991 runway collision between an Eastern Airlines B-727 and a Beechcraft King Air A100 in Atlanta Hartsfield International Airport (National Transportation Safety Board, 1991)
- The 1991 runway collision between a USAir B-737 and a Fairchild Metroliner at Los Angeles International Airport (National Transportation Safety Board, 1991)
- The 1991 in-flight structural breakup and crash of a Continental Express EMB-120 near Eagle Lake, Texas (National Transportation Safety Board, 1992)
- The 1992 aerodynamic stall and crash after liftoff of a USAir Fokker F-28 at LaGuardia International Airport (National Transportation Safety Board, 1993)
- The 1993 crash during approach of an Express Airlines II Jetstream 31 near Hibbing Minnesota (National Transportation Safety Board, 1994b)
- The 1994 aerodynamic stall and crash during approach of an American International Airlines DC-8 at Guantanamo Bay, Cuba (National Transportation Safety Board, 1994)
- The 1994 aerodynamic stall and crash during approach of an Atlantic Coast Airlines Jetstream 41 near Columbus, Ohio (National Transportation Safety Board, 1994)
- The 1994 crash during attempted go-around of a USAir DC-9 at Charlotte/Douglas International Airport (National Transportation Safety Board, 1995)
- The 1994 uncontrolled descent and crash during approach of a USAir B-737 near Alaquippa, Pennsylvania (National Transportation Safety Board, 1999)

Specific issues explored during the early 1990s included leadership, decision-making, communication, airport signage, and procedures for air traffic control (National Transportation Safety Board, 1991); visual performance, airport lighting, distraction, and procedural compliance (National Transportation Safety Board, 1991); visual performance, vigilance, workload, and supervision (National Transportation Safety Board, 1991); organizational culture, procedural compliance, and regulatory oversight (National Transportation Safety Board, 1992); visual performance (National Transportation Safety Board, 1993); communication, monitoring, and oversight (National Transportation Safety Board, 1994); decision-making, monitoring, scheduling, and fatigue (National Transportation Safety Board, 1994); planning, communication, monitoring, distraction, and response warnings (National Transportation Safety Board, 1994) (National Transportation Safety Board, 1995); and pilot response to unexpected malfunctions (National Transportation Safety Board, 1999).

In 1994, the NTSB Office of Research and Engineering published a study of 37 flightcrew-involved major accidents that occurred between 1978 and 1990 (National Transportation Safety Board, 1994). This study, which drew heavily upon human performance and operational information contained in NTSB accident reports, has been widely cited in the human factors literature. It contained a number of interesting findings including the following:

- The captain was the flying pilot in more than 80% of the accidents studied.
- Procedural, tactical decision, and monitoring/challenging errors were quite common.
- Almost half of the accidents occurred on the first duty day of a flightcrew pairing.
- Half of the accident-involved captains had been awake for over 12 hours.

The study's focus on flightcrew coordination, use of procedures, decision-making, monitoring, and time since waking reflects the strong emphasis on the concept of CRM that influenced safety work during the 1980s, and the agency's growing interest in flightcrew fatigue as a safety issue.

Investigations supported by the aviation human performance division during the late 1990s included the following:

- The 1996 wheels-up landing of a Continental Airlines DC-9 at Houston Intercontinental Airport (National Transportation Safety Board, 1997)
- The 1996 in-flight fire and crash of a Valujet DC-9 near Miami, Florida (National Transportation Safety Board, 1997)
- The 1996 in-flight loss of control and crash of an Airborne Express DC-8 near Narrows, Virginia (National Transportation Safety Board, 1997)
- The 1996 uncontained engine failure of a Delta MD-88 at Pensacola Regional Airport (National Transportation Safety Board, 1998)
- The 1996 in-flight breakup and crash of a TWA B-747 near East Moriches, New York (National Transportation Safety Board, 2000c)
- The 1997 crash during approach of a Korean Air B-747 near Agana, Guam (National Transportation Safety Board, 2000a)
- The 1997 crash during landing of a FedEx MD-11 at Newark International Airport (National Transportation Safety Board, 2000)
- The 1999 crash during landing of an American Airlines MD-82 at Little Rock National Airport (National Transportation Safety Board, 2001)
- The 1999 crash of an Egypt Air B-767 near Nantucket, Massachusetts (National Transportation Safety Board, 2002)

Issues explored included checklist design, procedural compliance, flightcrew training, and regulatory oversight (National Transportation Safety Board, 1997); equipment, flightcrew training, flightcrew procedures, maintenance procedures, and contract maintenance oversight (National Transportation Safety Board, 1997); stall warning systems, simulator fidelity, and stall recovery procedures (National Transportation Safety Board, 1997); maintenance inspection procedures (National Transportation Safety Board, 1998); eyewitness testimony (National Transportation Safety Board, 2000); briefing, monitoring, fatigue, and alerting systems (National Transportation Safety Board, 2000); stabilized approach procedures and aircraft handling during bounce recovery (National Transportation Safety Board, 2000); decision-making, fatigue, stress, and procedural noncompliance (National Transportation Safety Board, 2001); and mental health and a crash resulting from intentional pilot action (National Transportation Safety Board, 2002).

In 1996, the NTSB added an in-house medical officer to its staff (Garber, 1999). Previously, human performance and survival factors investigators were responsible for documenting and analyzing relevant medical issues with assistance from other U.S. government agencies (such as the Armed Forces Institute of Pathology or Civil Aerospace Medical Institute) as needed when complex issues arose. The new medical officer was not classified as an investigator, so the aviation human performance investigators remained responsible for collecting relevant medical information in aircraft accident investigations. The medical officer was also located in a different agency office and was quite busy, because he supported investigations in all modes of transportation. However, he worked closely with human performance investigators to analyze medical factors, and this gave the agency's human performance investigators more time to devote to the exploration of nonmedical factors underlying human error.

INCREASING SOPHISTICATION AND THE DEVELOPMENT OF INVESTIGATIVE GUIDANCE

Although CRM remained a paradigm for evaluating crew performance and was extended by various academic and industry safety specialists (Helmreich, 1996) (Helmreich, Merritt, & Wilhelm, 1999) (Klinect, 2005), the work of Reason (1990, 1997) became increasingly influential during the 1990s. Building on the work of Rasmussen (1983), Reason linked error types and cognitive control strategies to redundant layers of safety defenses embedded in a hierarchical organizational structure to create his now ubiquitous *Swiss Cheese* model. According to this model, all productive systems have redundant layers of defenses at the managerial, supervisory, and workplace level that are designed to guard against hazards. Hazards only lead to accidents when multiple layers of this defense structure are breached. Reason's framework eased the categorization of factors shaping human performance, linked them to organizational functions, and promoted consideration of a variety of accident countermeasures. It shifted the focus of prevention efforts off front-line operation and onto the organizational system, prompting increased consideration of organizational influences on behavior, including supervision, management, and organizational culture.

Reason's works profoundly influenced safety thinking for the next two decades. It helped shape the content of the first international guidance for investigating human factors in aircraft accidents, released in 1993 by the ICAO (International Civil Aviation Organization, 1993). ICAO, a UN agency established at the 1944 Convention on International Civil Aviation in Chicago, develops standards and recommended practices for aviation around the world. Guidelines spelled out in Annex 13 to the Convention on International Civil Aviation (International Civil Aviation Organization, 2016) are agreed upon by most of the world's nations.* ICAO's initial guidance was the product of an ICAO Flight Safety and Human Factors Study Group that was active from approximately 1989 to 2005 (Maurino, 2017). The group, which included representatives from the United States, Canada, Australia, United Kingdom, France, Japan, and Russia, sought ways to promote and facilitate investigation of human factors in aircraft accidents. After identifying a lack of international guidance on the topic, a decision was made to develop and release written guidance. The Australian Bureau of Air Safety Investigation and the Transportation Safety Board of Canada played a highly influential role in this process.

The resulting guidance material described the need for investigation of human factors, provided a methodology for conducting such investigations, and outlined how findings should be reported. The document's philosophical approach urged an *all-encompassing view* of the accident event. Investigators were urged to identify active and latent failures, and the defenses that failed to prevent them from propagating through the various layers of a productive system (including upper management, supervision, and the activities of front-line employees). For additional inspiration, investigators were referred to the work of Reason (1990), as well as the software–hardware–environment–liveware model developed by Edwards (1972) and refined by Hawkins (1987), which emphasizes the search for mismatches in the interface between people (liveware) and other major elements of an engineered system (software, hardware, environment, and other liveware). In contrast to earlier investigators who argued that "considerable training specialized training is required to effectively unravel and understand the mechanisms motivating human behavior" (Cierbelj, 1970), the circular argued that a human factors investigator needed only a sound aviation knowledge and some human factors training. Specifically, it asserted that

> The measure of the good human factors investigator is not his or her professional qualifications in behavioral sciences, but rather the ability to determine, with the help of specialists if necessary, what information is relevant, to ask the right questions, to listen to the answers and to analyze the information gathered in a logical and practical way. (International Civil Aviation Organization, 1993, p. 17)

* Minor differences are spelled out in statements of difference submitted to ICAO by individual member states.

The circular described an inductive reasoning process for analyzing human factors evidence and establishing cause–effect relationships. Investigators were encouraged to identify possible links using human factors research and couch their conclusions in terms of probabilities and likelihoods. An approach developed by the Australian Bureau of Air Safety Investigation was highlighted. It involved three steps: (1) testing for existence of a performance-shaping condition, (2) testing for influence of the condition on human performance, and (3) testing for the validity or relevance of the hypothesized relationship to the goal of accident prevention. The provision of this analysis structure addressed the previously-described gap in the NTSB's 1981 model, which did not specify an analysis method.

Strauch (1999) served as a chief of the aviation human performance division during the 1990s and was also heavily involved with the training of NTSB investigators. Strauch was influenced by the error taxonomies of Senders and Moray (1991) and the work of Reason (1990). Strauch also felt that human performance investigation could be improved by the adoption of an investigative protocol. He outlined his personal approach in a 2002 book (Strauch, 2002). In this book, Strauch defined human performance investigation as the application of a systematic study of the *relationships between antecedents and errors* and between errors and accidents (p. 170). Strauch focused on the need to cross-reference various forms of evidence to establish what happened and to draw on the available research literature to evaluate possible causal links. His writing was highly focused on the nuts and bolts of investigation, including the conduct of interviews and the interpretation of recorded flight data and other forms of investigative information. In line with Reason's and ICAO's thinking, he was also concerned with the exploration of company, regulatory, and cultural influences and played a leading role in the organization of a 2013 forum on the topic of safety culture.

Another engineering psychologist who briefly worked for NTSB in the 1990s, Doug Wiegmann, also went on to coauthor a book about investigating human factors (Wiegmann and Shappell, 2003). Wiegmann argued that the *Swiss Cheese* model could be applied even more systematically than had been advocated by ICAO. Wiegmann and Shappell's Human Factors Analysis and Classification system hewed closely to Reason's (1990) model of active and latent failures. It specified four layers of factors that could affect safety in a complex system: (1) unsafe acts of operators, (2) preconditions for unsafe acts, (3) unsafe supervision, and (4) organizational influences. Wiegmann and Shappell (2003) demonstrated high inter-rater reliability when coding the findings of completed accident investigations. However, these codings were applied retroactively for gaining insight into accident investigations that had already been completed (Wiegmann and Shappell, 2001). The model did not specify precisely how human performance investigation was to be conducted, or how linkages between cause and effect should be tested and established. This made the model less useful for conducting an investigation.

Strauch (2015) opined that human performance investigation at the NTSB remained largely unwedded to any particular theory or method of human factors and that accident analysis at the agency was "legalistic, based on logic and internal consistency and the preponderance of evidence" and dependent on the research literature available at the time. After reviewing the works of Heinrich (1941), Perrow (1999), Dekker (2002), Leveson (2004), and Griffin et al. (2010), he argued that "no model has been proposed that appears to have replaced the methodology currently employed for their effectiveness in explaining operator performance in accident investigation scenarios." Strauch argued that a failure to coalescence around any single theoretical model or approach stemmed from the fact that theoretical models could never truly replicate the complexity of accident causation, and that the highly varied underpinnings of causation meant that the theoretical model that was best suited to analyzing a particular accident would naturally vary. He predicted that researchers would continue to apply models of accident causation after investigations had already been completed, with the relevant issues identified by skilled investigators operating from expert knowledge and experience.

Evan Byrne, who joined the NTSB in 1996 and served as the chief of the NTSB's aviation human performance division from 2001 to the present, inherited from Strauch the responsibility for training NTSB investigators in the investigation of human factors. He revised the 1981 human performance investigation model categories in 2005, condensing them from six to the following four: (1) physiological, (2) behavioral, (3) cognitive, and (4) workplace environment factors. Byrne advocated careful study of standards for performance; examination of the characteristics, recent activities, and actions of key personnel; a close look at the workplace environment (both physical and social) in which the performance was occurring; and the identification of limitations of the human cognitive system that could help explain any errors that were documented. Like Strauch, Byrne urged consideration of team, organizational and cultural factors on behavior, leaving it to individual human performance investigators to seek guidance from the published works of authors such as Reason (1997) and Vaughan (1997). However, the human performance investigation guidance contained in the NTSB's Major Team Investigations Manual (2002) has not been revised to reflect these changes.

In 2014, ICAO released the aforementioned updated guidance on the investigation of human performance in aircraft accident investigation. (International Civil Aviation Organization, 2014)

In addition to specifying the objectives of human performance investigation. ICAO urged human factors investigations to be systematic, fully integrated into the broader investigation, and based on a systems-oriented approach. Additional guidance is available in the *Manual of Aircraft Accident and Incident Investigation* (International Civil Aviation Organization, 2014), *Human Factors Training Manual* (International Civil Aviation Organization, 1998), and Circular 240 (International Civil Aviation Organization, 1993).

THE RISE OF SAFETY MANAGEMENT AND DATA-DRIVE SAFETY EFFORTS

An important national development in the investigation of aviation safety issues, including those related to human factors, was the formation of a White House Commission on Aviation Safety and Security in 1996, a month after the accident involving TWA flight 800 (National Transportation Safety Board, 2000). This commission was chaired by U.S. Vice President Al Gore and included participation from numerous other public officials, including the chairman of the NTSB (White House Commission on Aviation Safety and Security, 1997). Facing a predicted tripling in the number of airline passengers over the next decade, the Commission expressed concerned about a potential increase in the frequency of accidents. It advocated aggressive action to reduce the already low accident rate by 80%. To accomplish this goal, the commission urged several actions. Some of these actions were technical, such as advocating more widespread installation of enhanced ground proximity warning systems. Others were more abstract, such as urging the formation of a government-industry partnership to improve and integrate research, standards, regulations, procedures, and infrastructure. A National Civil Aviation Review Commission report published months later reiterated this and urged the FAA and industry to develop a comprehensive integrated safety plan that would establish priorities based on "objective, quantitative analysis of safety information and data" (National Civil Aviation Review Commission, 1997).

The Commercial Aviation Safety Team (CAST), and FAA-industry partnership, was established as a result of these recommendations. Formed in 1998, CAST's mission was to "to significantly increase public safety by adopting an integrated, data-driven strategy to reduce the fatality risk in commercial air travel" (Commercial Aviation Safety Team, 2017). In the two decades since its founding, CAST has pioneered methods for systematically analyzing safety-related information and converting its findings into tangible safety improvements undertaken by the aviation industry. By leveraging increasingly large repositories of confidential operational safety data, accident reports, and other sources of data, CAST has completed analysis projects on major areas of aviation risk with human factors components, ranging from controlled flight into terrain accidents (Commercial Aviation Safety Team, 1998), to approach and landing accidents (Commercial Aviation Safety Team, 1999), to in-flight loss of control accidents. CAST studies produced a litany of related safety recommendations on which the industry has actively worked. CAST has been a major success story for aviation safety improvement and government-industry cooperation.

CAST's efforts have been complementary to the rise of the safety management system, a paradigm that involves managing safety by measuring safety indicators so that it can be controlled like other business processes. Since CAST was formed, standards for safety management systems (SMS) development and implementation have been created for use by individual operators and national regulatory agencies (Federal Aviation Administration, 2010; International Civil Aviation Organization, 2012). The rise of SMS is an important development in the history of aviation safety because it has move the locus of control from reactive accident investigations and centralized government control to proactive analysis and decentralized control. This shift, in turn, resulted from two earlier changes, a move toward the deregulation of airlines that began in the 1980s, and the development of increasingly sophisticated technologies for monitoring and recording the progress of airline flights and flagging safety-related incidents or deviations from a desirable range of operating parameters. The FAA has been intimately involved as a partner in such efforts, such as the Aviation Safety Information Analysis and Sharing system. Until recently, the NTSB was excluded from direct participation due to concerns about the confidentiality of such sensitive data and an unwillingness to involve a transparent public agency in such analysis.

THEORETICAL PERSPECTIVES

Views on human performance evolved considerably over the last 100 years. The late nineteenth and early twentieth century saw much attention paid to the identification of ideal methods for performing work and the selection of workers who were best-suited for particular tasks. Rapid advances in technology and the massive mobilization of personnel that occurred during World War II, however, caused the emphasis to shift toward examination of the "psychological capacities and limitations of individuals" and the design of equipment that was more compatible with their needs (Fitts, 1947). The impact of this shift on perspectives in aviation safety is evident in the writing of McFarland (1946), who argued that although studies of air transport accidents indicated that 75%–85% could be attributed to human error, "neither the operating characteristics of the plane nor the performance of the pilot can be considered as completely separate variables."

This change in the approach to development of technological systems gave rise to the human factors profession (Sanders & McCormick, 1993), and it was accompanied by a shift in perspectives on human error. Reason (2000) has made the distinction between *person* and *system* views of error. According to Reason, the person view of error focuses on the personal accountability of individuals and blames them for forgetfulness, inattention, or moral weakness, whereas the system view sees error as part of the human condition and emphasizes the role of system design in preventing and mitigating error. Similarly, Dekker (2014) has written about the shift from an *old view* to a *new view* of error. According to Dekker, the *old view* regards human error as the cause of accidents, whereas the *new view* sees it as the consequence of upstream factors involving the use of technology and the design of tools and tasks. Although Dekker describes this shift as the natural progression of safety thinking, Reason (2015) argues that the person view is the oldest and still the most commonly held view of error.

System-oriented views of human error are widely embraced in the human factors community, but they are not universally accepted. The person model is particularly appealing in cultures that emphasize personal responsibility and freedom of choice. It is also reinforced by various human cognitive biases. These include the hindsight bias (a tendency to see outcomes as more predictable after they have occurred) and the fundamental attribution error (a tendency to attribute others' failings to personal characteristics while de-emphasizing contextual factors). Additional biases include the *just world* hypothesis, which is the tendency to believe that bad things happen to bad people, and outcome bias, which is a tendency to discount the idea that bad outcomes can result from good decisions. From an organizational standpoint, placing blame on individual operators is less complex and consumes fewer investigative resources. It also compartmentalizes responsibility, reducing the likelihood that powerful interests will be threatened, and it may provide reassurance to an anxious public concerned about finding quick solutions to avoid the potential for recurrence.

The person model has not been particularly useful from the standpoint of learning about safety-related risks and preventing accidents, however. It leads to premature closure of investigations that stop short of identifying systemic issues underlying recurring patterns of accidents and, therefore, to less learning and fewer, less useful safety recommendations. For this reason, the charters of many safety organizations include a provision specifying that the purpose of a safety investigation is the identification of safety hazards and the development of recommendations for improvement of safety, rather than allocation of blame. Still, accident investigators are human. Many have had little formal training in psychology or human factors, and all organizations are subject to the pressures and biases described earlier. For these reasons, the person model survives—even among members of the professional accident investigation community.

NOTABLE SUCCESSES

One outcome of decades of professional accident investigation has been the encouragement of new safety technologies. Enhanced ground proximity warning systems have reduced the risk of controlled flight into terrain accidents, and traffic collision alerting systems have reduced the risk of midair collisions, and ground radar surveillance systems such as ASDE-X have improved controller awareness of airport surface traffic. Although the evolution of aviation technology has introduced new human factors challenges, such as how to keep humans in the loop when more and more of their cognitive work is being shared with machines, it has also contributed to extremely high levels of safety that exist in the airline industry today. In fact, the system has become so safe that several recent years have passed with no fatal accidents among major U.S. airlines, despite the carriage of hundreds of millions of passengers.

CONTINUING CHALLENGES

Human factors, in general, is concerned with "understanding of interactions among humans and other elements of a system" and the application of "theory, principles, data, and other methods to design in order to optimize human well-being and overall system performance" (International Ergonomics Association, 2017). Moreover, human, organizational, and systemic factors are ubiquitous causal factors for accidents in hazardous industries, meaning human factors expertise is critical to understanding accidents. However, most accident investigators are technical or operational specialists (Reason, 2002), which sometimes leads to a lack of familiarity with human factors.

In the 1940s, the division of labor between humans and machines was relatively straightforward. Humans and machines shared responsibility for simple control tasks, and humans had exclusive domain over complex, higher order tasks. Human factors specialists of the day devoted attention to determining the optimal arrangements and physical properties of controls and displays to minimize pilot workload and errors (Fitts, 1947). The introduction of microcomputers led to more automation and more complex technological systems and new pathways to failure, and the issue of mismatches between humans and technological systems has become more complex.

ICAO also asserts that the “sole objective of the investigation of an accident or incident shall be the prevention of accidents and incidents .... It is not the purpose of this activity to apportion blame or liability.” In this investigator’s personal experience, however, it appears that the public, journalists, and even some aviation industry professionals can have difficulty separating the search for safety-related explanations from allocation of blame or responsibility.

Although safety investigation is focused on learning from failure, blame fulfills needs that are not necessarily aligned with this goal. The inclination toward a blame-oriented perspective may stem from cultural views about free will and professional responsibility, cognitive biases, organizational resource limitations, or from reasons of administrative convenience (Maurino, Reason et al. 1995). As a result, there is sometimes a significant gap between the views of the human factors investigator and the views of other constituencies to an accident investigation. Successfully navigating this situation requires a sophisticated understanding of human factors and a well-developed interpersonal skillset. As few accident investigation agencies are led by human factors experts, most human factors investigators cannot rely on positional authority to exert influence.

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