Review and Analysis of the Effects of Major Aviation Accidents in the United States on Safety Policy, Regulation, and Technology

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The authors reviewed civil air transport accidents over a 15-year period (1988-2003) and arrived at milestone accidents. The impact of these milestone accidents on aviation safety developments in policy, regulation and technology are analyzed here. The analysis shows that these accidents have led to significant changes in these three areas. However, it is concluded that the outcomes were reactive as opposed to proactive solutions. Indicators of change are U.S. Congressional and Federal Aviation Administration records and other published information. The impacts of milestone accidents are shown using a timeline format to demonstrate various sets of outcomes and their interrelation over time.

INTRODUCTION

The growth and increasing complexities of the U.S. airline industry and its subsequent deregulation in 1978 have resulted in aviation accidents having a significant impact on aviation regulation, policies and technological developments. Some past accidents clearly stand out as milestones resulting in historical and fundamental changes in aviation. Similar trends and milestone events can be observed in other industries, such as the Three Mile Island accident for the U.S. nuclear industry or the Bhopal accident involving a DuPont chemical plant.

This paper grew out of an interest in root causes of key aviation safety developments and uses of graphical display tools to present that information to the aviation community. To determine milestone accidents, all accidents during a recent 15-year period were reviewed to evaluate the effects of accidents on regulation, policies and technology. This paper describes the process of selecting those milestones and reviews the resulting outcomes. The milestone accidents are described in brief, followed by a series of discussions on significant policy, regulation, and technology outcomes. The result of this research is a *timeline* of milestone aviation events and the resulting outcomes in policy, regulation and technology.

The timeline is a graphical display tool intended to function as a reference for succinctly displaying a large amount of information relating aviation accidents and safety-related outcomes. A sample of the aviation safety timeline is presented along with conclusions drawn from the research. Among them, the timeline depicts costly and valuable lessons that many countries may find useful for the continued development of their air transport systems. While all milestone accidents involve fatalities, accidents with low fatality also led to significant changes in policy, regulation and technology. The authors hope to cast an informative and factual light on milestone accidents so that the aviation community can better understand what the outcomes from these accidents were, when these outcomes occurred, and how they occurred in relationship to one another.

LITERATURE REVIEW

Birkland's (2004) idea of "focusing events" formed the basis for describing and determining this paper's milestone aviation safety accidents. Focusing events serve as a wake-up call to attract attention to major public problems and lead to searches for solutions because they can be used to demonstrate the existence of policy failure. Birkland (2004) distinguishes between two types of focusing events: an event that would not have happened or would not have been so severe "if only" something had been done versus an event that serves groups that were already warning of the existence of a problem. These are events that clearly show a pattern of existing problems that have been argued as a precursor to an accident. Along with the argument for policy failures comes a search for answers and, in particular, an attempt to apply these so-called lessons of an event to mitigate the impacts of such future events (Birkland 2004).

Focusing events have also been the focal point of research in aviation safety. Walters and Sumwalt (2000) looked at major air carrier accidents, regional airline accidents, military accidents and general aviation accidents when applying this concept. Walters and Sumwalt (2000) selected accidents across these aviation sectors if they fit the criteria of "mishaps where the system failed" and a catastrophic loss of life or injury occurred. Cobb and Primo (2003) stated that crashes can trigger changes in airline safety by focusing attention on particular areas of safety, thereby forcing the Federal Aviation Administration to address them. Focusing on major airlines and commuter air carriers, Cobb and Primo (2003) selected 27 accidents during the 1990s and limited their outcomes to effect on policy (10 of these outcomes overlap with this paper's milestone accidents). Of the 27, three accidents are described in great detail. These three accidents (USAir flight 427, ValuJet flight 592, and TWA flight 800) are characterized as crashes having no survivors. When examining the outcomes, Cobb and Primo (2003) incorporated a wide array of information, including: speed of investigation, result, media targets, presidential and congressional involvement, airline response, manufacturer response, and new regulations.

This paper also examines focusing events in aviation safety. While Walters and Sumwalt (2000) looked at four sectors of aviation, this paper narrows its focus to air carrier accidents. Second, this paper takes another approach to the selection process. Instead of selecting an accident based on cause, the approach used here focuses on the outcomes. In particular, we focus on the accidents that had significant outcomes in policy, regulation, and technology, regardless of the cause. In doing so, this paper shares the same general focus on outcomes as the Cobb and Primo (2003) paper. However, it adds technological developments to the analysis.

Cobb and Primo (2003) include manufacturer (airframe) responses, which include technological developments. However, we find this scope to be narrow. Therefore, we include safety developments including avionics, engines, radar, and general safety equipment to name a few that can be found in many areas of aviation. Finally, while Cobb and Primo (2003) focused most of their attention on three accidents that had no survivors, this paper attempts to give equal weight to accidents that have low number of fatalities as those that have high fatalities.

The methodology for displaying research results and conclusions can be as important as the crash selection process. The incorporation of a timeline methodology to display findings has been used by Rubin et al. (2003) for the "Terrorism Time Line" (TTL). The TTL is a graphic outline that depicts major terrorist events and their affects on laws, regulations, practices, expert systems, as well as organizational changes related to these events during the last two decades. We use a similar method to display our research findings. This paper is the first to apply this graphical tool to aviation literature.

Existing tools could have been used, but charts, lists or tables alone lack key features of the timeline methodology. Cobb and Primo (2003) use columns and rows in a table format to visually display the outcomes of accidents. The information displayed by this format has limited value as a reference tool. The row of outcomes for presidential and congressional involvement, for example, lack detailed reference numbers as does the row for new regulations. The lack of detailed reference information is critical as this paper seeks to develop a thorough and useful reference for the aviation community. Second, the outcomes in this format do not include a time reference, so the reader does not know when they occurred or how long it took for their completion. Third, the outcomes are not displayed in a manner that juxtaposes them over time.

While we use charts, lists, and tables throughout this paper, the timeline approach presents the connections and links between these separate tools. This allows for various sets of related outcomes to be presented side-by-side on the same scale. Juxtaposing outcomes makes the timeline a better tool to display historical developments in aviation because it allows for a complicated and sometimes esoteric development to be succinctly displayed in a manner that is concise, interesting and thought provoking. This juxtaposition characteristic also gives the timeline an advantage when presenting long-term impacts because one can easily "follow" a change over an extended time period. Just as important, the timeline displays outcomes with unmatched visual impact, something that a chart, list, or table (alone or in combination) cannot achieve. Ultimately, the research presented here combined with the timeline display is an invaluable contribution to aviation literature because it provides the connections between hard-to-find information, hopefully providing it to the aviation community and layman in an interesting, factual and visually compelling way.

RESEARCH METHODOLOGY

Analysis of accident data and impact of accident morphology on aviation safety has always been challenging because of statistical limitations, system complexity, and difficulties associated with accident investigations. Accident analysis has always been used to justify distribution of resources and development of new technologies, regulations and policies. However, the conclusions drawn from such analyses depend on what type of operation and accidents are considered. Motevalli and Salmon (2005) discuss this in some detail. To account for these limitations, the set of accidents considered in this paper is all-inclusive to avoid initial bias.

The AirClaims database (2004) for a 15-year period of 1988-2003 was used to establish a large pool of aviation safety events based on the following criteria:

- Scheduled passenger jet flights,
- Payload capacity more than 7,500 pounds or/and passenger capacity greater than 30 seats,
- U.S. carriers in domestic or international flights, and
- Accidents occurring in the U.S. territory involving foreign carriers.

Security events that lead to aircraft crashes were not considered. Thus, the 1988 Pan Am 103 bombing, or the extraordinary events of Sept. 11, 2001, are not included in this initial data set. AirClaims is a loss-based database for insurance purposes, all events regardless of fatality resulting in substantial damage and property loss are noted.

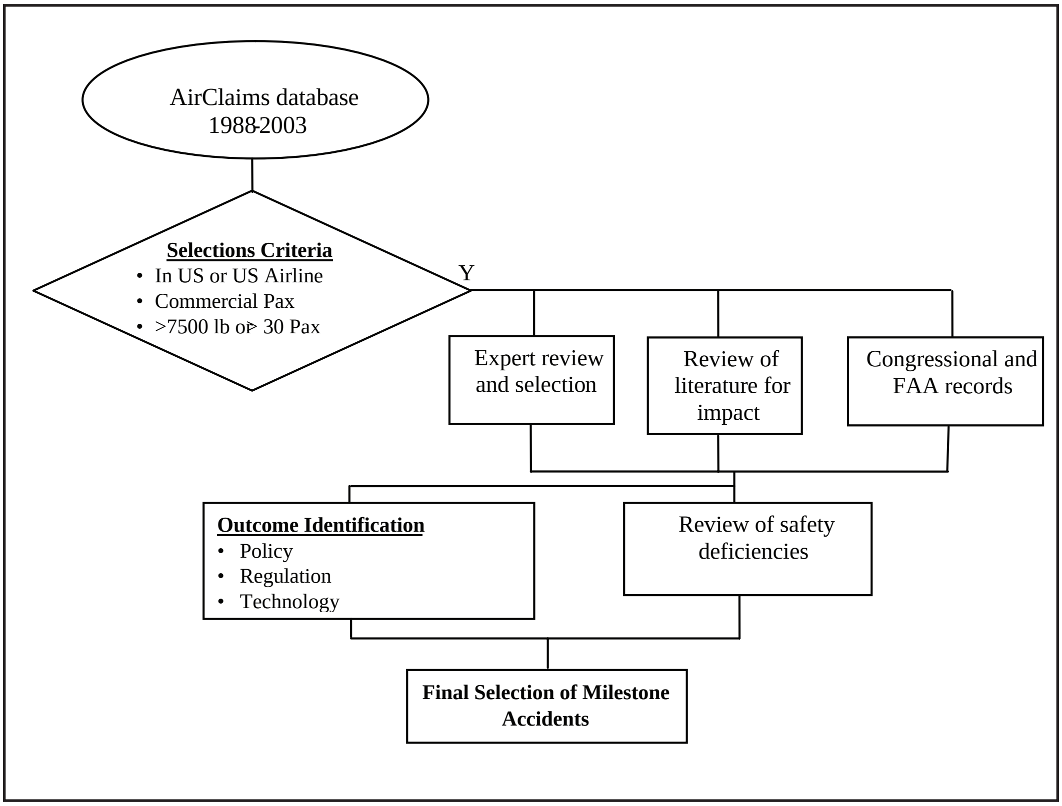
The initial search resulted in a pool of 137 events complete with a basic level of details. The AirClaims database does not designate one accident to be more significant than another. Thus, more information for each of these events was gathered using several Internet-based aviation accident search engines (Airdisaster.com 2004 and Aviation-Safety.net 2004). For example, a Korean Airline flight encountered volcanic ash resulting in a flame-out of all four engines during a flight (1996) is included in the data set, although the engines were re-started and there were no fatalities or injuries and thus this event would not be classified as an accident. (The accepted definition of an accident based on NTSB and FAA description, although slightly different, is an event which results in fatality, injury or substantial loss of property.)

Fourteen experts with various backgrounds in aviation safety, such as law and regulation, accident investigation, human factors, operational and safety management in airlines, were asked to review the list of 137 events with some basic details to determine which could be considered "milestone" according to the following criteria: aviation safety related accidents which have led to significant outcomes in the areas of policy, regulation, or technology. For clarity, policy was defined as a plan of action adopted by an organization; regulation as a rule or restriction, and technology as an applied system that serves as a solution to a particular safety issue across the entire industry. Major accidents and their outcomes were evaluated with respect to these three areas. Each of the six experts who replied selected accidents that in their view were milestones and indicated their reasons for doing so. In total, 26 of the pool of 137 events were designated as "milestone" by the experts. A number of accidents were designated as milestone only by one expert. Any accident that was selected at least once was further reviewed for outcomes affecting policy, regulation and technology.

The review of the 26 accidents included details of the accidents and aircrafts involved from Airdisaster.com and Aviation-Safety.net. The probable cause was based on the National Transportation Safety Board (NTSB) accident database or the responsible foreign government agency where applicable (NTSB 2004). Evidence of significant impacts of an accident normally occurs over a span of several years and the determination of the probable cause of that accident is critical. Our research examined Congressional actions, FAA regulatory actions and implementation of technologies since 1988. Clearly, accidents occurring in 2003 may not have had adequate time to make an impact. But, the process is as important here as the actual accidents being designated as milestones.

Figure 1 depicts the process that was followed for the selection of milestone accidents. Based on the criteria established for impact, expert opinion and the volume of activities generated by any of these accidents, the list of milestone accidents was reduced. In addition to the effect of each accident on policy, regulation, and technology, the accident investigations and the probable causes also reveal areas of safety deficiency, for example human error or mechanical failure. Taken altogether, the final list of milestone accidents was reduced to 14. All these accidents along with four other accidents that were considered in a previous paper (Lagos et al. 2005) are included in Appendix A (accidents 1, 3, 4 and 12 are listed in the appendix for completeness but are not considered milestone). The discussion that follows shows that fatal accidents, by their inherent seriousness, seem to have the highest impact. However, it should be noted that fatality may be the necessary, but not sufficient reason for the level of impact an accident may have on changes in policy, regulation and technology.

Figure 1: Process for Selecting Milestone Accidents



MILESTONE ACCIDENTS & CATEGORIZATION OF SAFETY ISSUES

Each of the 14 milestone accidents was examined as an individual case study including the body of information about that accident. Accident details, policy outcomes during the corresponding congressional session, public laws complete with dates of promulgation, lists of regulatory responses along with dates of their enactment, and technological developments complete with dates of their introduction were reviewed. The main objective for selecting any milestone accident was not simply its designation, but identification of key safety issues that prompted it to be a milestone event. Because many of the safety issues from these accidents overlap, they were categorized into groups. The general categories are the classifications commonly used by NTSB, FAA and similar organizations in describing safety deficiencies in accident investigation reports. Clearly, there are variations in these designations even in fatal accident reporting (Motevalli and Salmon 2004). The safety issues are the link between these milestone accidents and the larger context of policy, regulation and technology. The significant outcomes in this larger context have resulted in improved policy, regulations, and technology tools to prevent a reoccurrence of the safety issues associated with these milestone accidents.

Compilations of the safety deficiencies for each of the milestone accidents are shown in Table 1. Interestingly, a large number of accidents share the common deficiencies of *design*, *FAA oversight*, and *maintenance*. This is logical as FAA oversight is required for the design stage through aircraft certification and in the maintenance process. Furthermore, it also points to the fact that design plays an important role in the maintenance regime of the aircraft. Table 1 makes it relatively easy to quickly examine a number of safety issues related to these accidents, but it is not intended to be all inclusive.

Table 1: Selected Categories of Safety Issues

	Design	Aging Aircraft	Mechanical Failure	FAA Oversight	Human Error	Maintenance	Weather
1988 – Aloha Airlines FL243		✈		✈	✈	✈	
1989 – United Airlines FL811	✈					✈	
1989 – United Airlines FL232	✈				✈	✈	
1990 – Avianca Airlines FL52				✈			
1990 – Northwest Airlines FL1482	✈					✈	✈
1991 – USAir FL1493				✈	✈	✈	
1991 – United Airlines FL585	✈		✈				✈
1994 – USAir FL427	✈		✈				
1995 – American Airlines FL 965	✈			✈	✈		
1996 – ValuJet FL592				✈	✈		
1996 – Trans World Airlines FL800	✈	✈				✈	
1997 – Korean Air FL801	✈			✈			
1999 – American Airlines FL 1420				✈	✈		✈
2000 – Alaska Airlines FL263	✈			✈		✈	

OUTCOMES – POLICY, REGULATION, AND TECHNOLOGY

Measuring outcomes and impacts of milestone accidents in the three areas of policy, regulation and technology inherently varies due to the nature of each of these areas. While identifying technology outcomes because of an accident can be done, for example, by identifying the specific systems, devices or design changes, clear indicators of outcomes in the policy area are more difficult to establish.

Because the U.S. government is responsible to set policies in aviation safety, U.S. Congressional responses concerning aviation safety are some of the best indicators of policy outcomes. These responses are either in reaction to a proposed initiative by the executive branch, as a matter of oversight on government activities, or in response to public inquiries. Indicators of Congressional response include public laws and hearings in the Senate, House and Joint Committees. Congressional sessions cover a two-year period, so policy outcomes are grouped accordingly.

Regulatory actions by the FAA are the best indicators for measuring outcomes in the area of regulations. In this paper, these indicators include Airworthiness Directives (AD), Advisory Circulars (AC), and Amendments to the Federal Aviation Regulation (FAR - part of the Code of Federal Regulation or CFR). Also included are Bulletins or other documents, which include Action Notices, Final Rules, Letters, Notices, Orders, Plans, Policy Statements and Reports or Revisions to particular manuals. However, the process of determining a connection between an accident and regulatory outcomes can be esoteric. The FAA database of regulations does not make a connection between a regulatory tool and an accident. Thus, one cannot search the regulatory database by entering a flight number or airline name. To determine connections, one has to follow a circuitous path. The *NTSB Safety Recommendations to the FAA with FAA Responses* (2004) in the National Aviation Safety Data Analysis Center website were used as a starting point followed by reviewing FAA responses written in a letter format. This latter approach is the only way one can one find references to consequential and specific regulatory outcomes.

The *NTSB Safety Recommendations to the FAA with FAA Responses* (2004) was also used as a starting point to further examine outcomes in terms of technology. In addition Congressional and FAA documents were examined for references to particular technologies. Using these references, a variety of sources, including reports, news and journal articles were used to obtain information describing which technologies were developed or implemented as a result of specific milestone accidents. A full demonstration of the relationship between the milestone accidents and the three impact areas are described in Lagos et al. (2005) and can be obtained from the George Washington University Aviation Institute in its updated form. Selected outcomes between the milestone accidents and policy, regulation and technological developments are displayed in portions of the aviation safety timeline shown is three consecutive figures (Figure 2a, b, c). Because of space limitations, not all outcomes can be displayed. These figures represent examples of development of this timeline.

Policy Response

Effect of accidents on policy response is diffused due to the length of time it takes for policy actions. In this segment, relationships between a number of accidents and different areas of impact such as oversight, maintenance, aging aircraft and human factors are specifically discussed. These same areas are also the focal point of regulatory response and technology.

Oversight: FAA oversight was stated as an important safety issue in more than a half of the NTSB aviation accident reports of the milestone accidents. The FAA's oversight responsibility puts the FAA in a unique position, opening it to public criticism when accidents occur. The intensity of public criticism can be measured by news reports, articles and books written on the subject (Sakata 2003). A policy metric may be the number of Congressional hearings in regards to aviation safety.

Figure 2a: Aviation Safety Timeline: Examples of Impacts of Accidents on Policy, Regulation and Technology

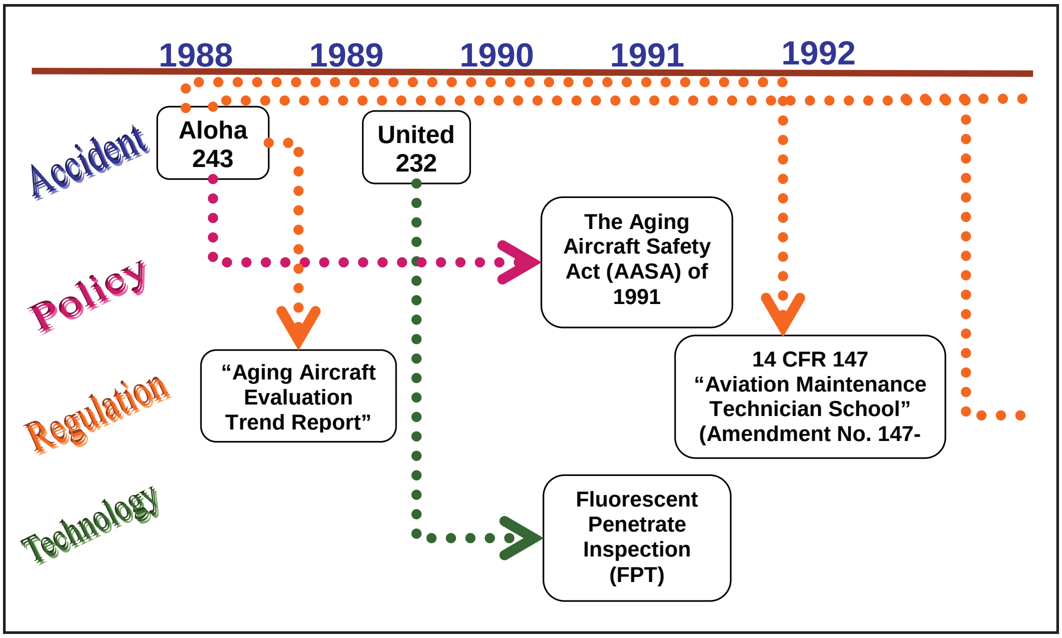


Figure 2b: Aviation Safety Timeline: Examples of Single Accident on Policy, Regulation and Technology

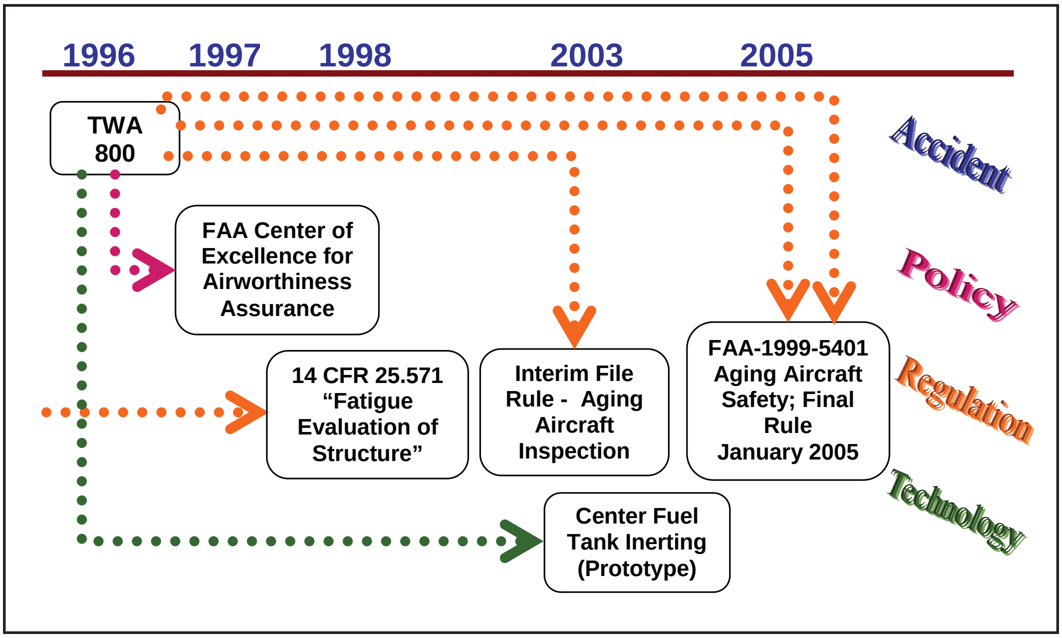
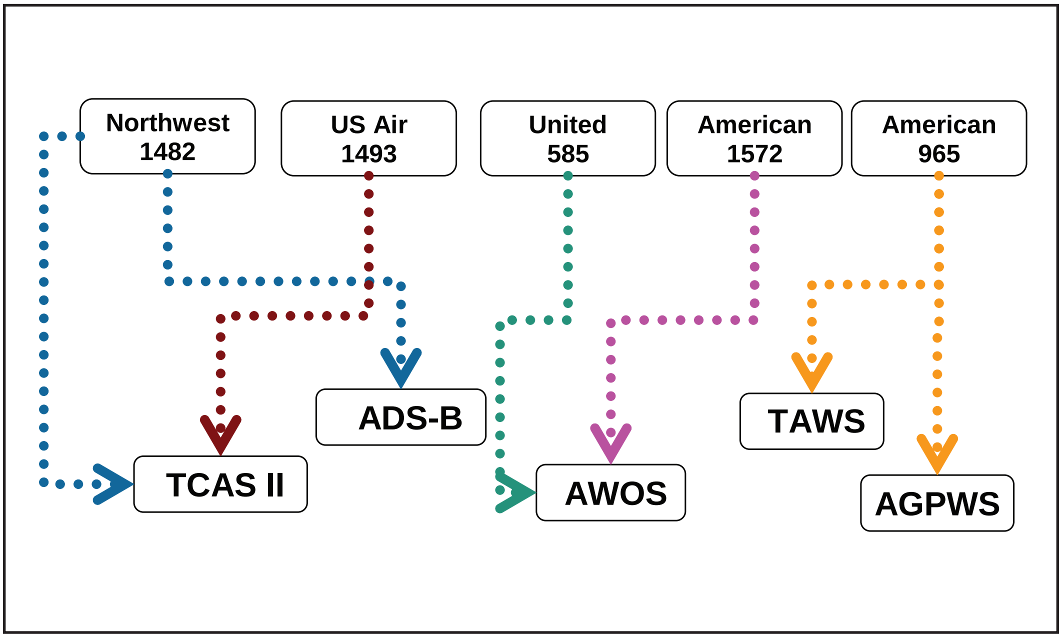


Figure 2c: Aviation Safety Timeline: Examples of Technology Outcomes from Several Accidents



Note: An accident may relate to more than one outcome. Also, more than one accident may contribute to a single outcome. See Table 3 for the definitions of the acronyms shown here.

Figure 3 describes the Congressional policy response during the 15-year period in terms of the number of hearings and laws related to aviation safety with both number of accidents and milestone accidents per Congressional session shown.

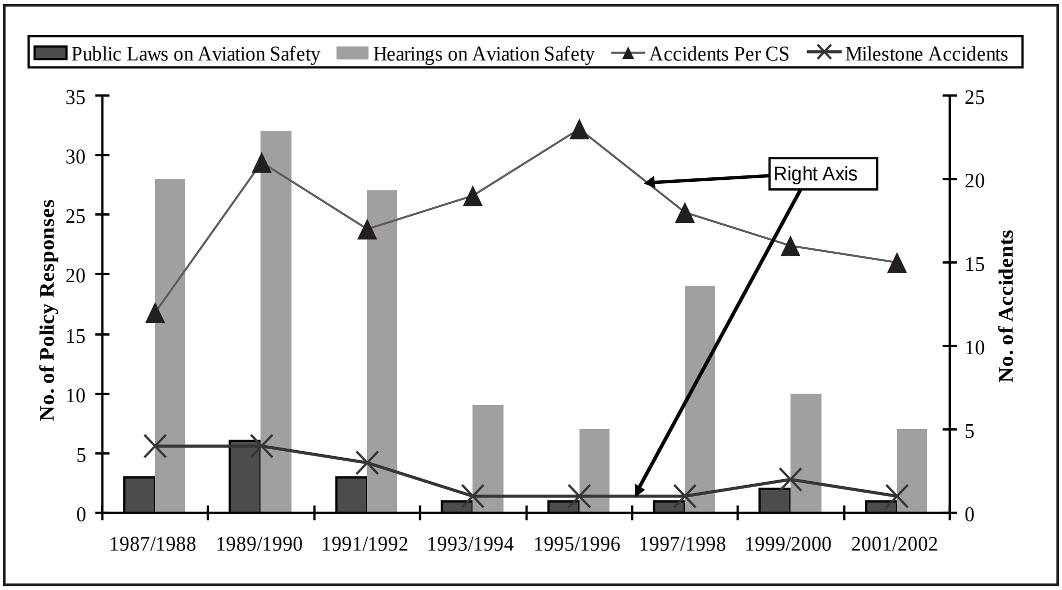
In total, 139 hearings were held and 18 public laws were issued. During the 100th Congressional session (1987-1988), a number of hearings in the Senate, House and joint committees were held concerning FAA oversight issues. Congressional criticism of the FAA's ability to conduct effective oversight, in light of the consequences of the deregulated air transport industry, was prevalent at the beginning of the 15-year period. The years of 1988 and 1989 were characterized by widespread criticism of FAA's ability to ensure safety in a rapidly growing air transport industry. Hearings on the matter continued through the 101st Congressional session (1990-1991). The lack of FAA oversight of foreign air carriers received significant attention after the Avianca flight 52 crash in 1990. In 1992, the FAA established the International Aviation Safety Assessment (IASA) Program which focuses on a country's ability to adhere to international standards and recommended practices for aircraft operations and maintenance developed by the International Civil Aviation Organization (Kolker 2001). Through the 103rd Congressional session (1994-1995), the number of hearings decreased, although safety and deregulation of the airline industry was a significant topic of discussion. No public laws were singularly enacted during the 15 years for the purpose of changing oversight, though several laws, including authorization legislations, contained elements that required the FAA to address a number of other safety issues. Eventually, the belief that deregulation was unsafe, along with criticism of the FAA's oversight abilities subsided. As the rate of accidents (both for United States and worldwide) has declined, so has the number of public laws and hearings. Interestingly, the number of milestone accidents has also declined. The period of decline corresponded to an increasing amount of air traffic and growing complexity of the air traffic system.

Maintenance: Some of the key areas of aviation safety are maintenance and aging aircraft which can be considered as two separate issues. However, it is clear that aging aircraft issues have influenced the procedures for maintenance and inspection over the examined 15-year period. The sheer number of hearings during this period is indicative of the significance of this safety issue in Congress. Nineteen out of the total 138 hearings were dedicated to maintenance and aging aircraft. Seven different hearings on aging aircraft were held beginning in 1988 as a result of the Aloha Airlines flight 243 accident. Although operators and manufacturers already had become concerned with airplanes that were reaching their "design life," the Aloha accident in 1988 took those in civil aviation by surprise (Tripp 2001). A significant amount of attention focused on the characteristics and causes of structural aging. Additional hearings were held following the explosive decompression accident of United Airlines flight 811. Passage of the Aircraft Catastrophic Failure Prevention program under the Omnibus Reconciliation Act of 1990 (PL101-508) further expanded the FAA research mission (FAA 1999). In 1991, Congress passed the Aging Aircraft Safety Act (PL102-143).

There were only five hearings held on maintenance, fewer than those held on aging aircraft. However, consideration of an Aviation Safety Whistleblower Protection Act during the 101st Congressional session (1989-1990) was significant because it indicated a growing concern with inspections. Immediately following the 1996 TWA flight 800 accident, the Presidential Commission on Aviation Safety and Security in the 21st Century (also known as the Gore Commission) was convened. This Commission made several recommendations concerning aging aircraft safety issues. By the 105th Congressional session (1997-1998), the FAA had established a Center of Excellence for Airworthiness Assurance, which included inspection, maintenance and repair as academic and industry research focuses.

Human Factors: Human Factors became another area of concern at the policy level beginning with the 100th Congressional session (1987-1988). Following the Aloha flight 243 accident, Congress passed the Aviation Safety Research Act of 1988, which mandated that the FAA augment its Human Factors research in practically all areas of aviation, including aircraft, cockpit, air traffic system, as well as maintenance and inspection. Although this law addresses issues well beyond the structural integrity and airworthiness of airplanes, the Aloha accident certainly prompted its initiation and passage during 1988.

Figure 3: Number of Policy Responses and Number of Accidents per Congressional Session

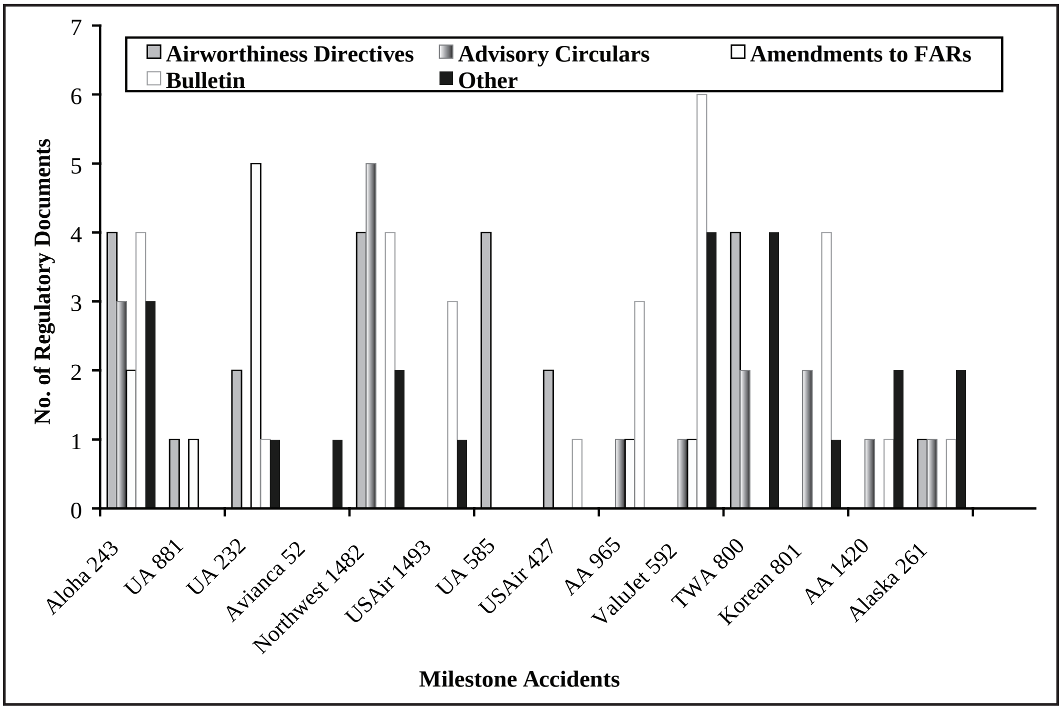


Note: CS = Congressional Session

Regulation Response

The regulations for aviation safety issued by FAA and that agency's oversight are at the core of more than half of the milestone accidents. Among those accidents, the Aloha flight 243 and ValuJet flight 592 accidents brought widespread public criticisms on FAA oversight. In fact, the criticisms were so intense that the day after the ValuJet flight 592 accident, the Flight Standards Service (an arm of the FAA's Regulation and Certification Organization) ordered all Flight Standards District Offices to "stand down" for one day and to review their internal policies, procedures, and methods of operations. Following an additional 90-Day Safety Review, which examined federal regulations and FAA's oversight of commercial airlines engaged in substantial contracting out of maintenance and training functions, the FAA implemented a system safety approach to certification and surveillance oversight, known as Air Transportation Oversight System or ATOS (FAA 2004). FAA, as the oversight authority, has used regulatory tools to respond to safety issues. Figure 4 shows the FAA regulatory responses for each of the 14 milestone accidents, organized by Airworthiness Directives (ADs), Advisory Circulars (ACs), Amendments to the Federal Aviation Regulations (FARs), Bulletins, and the other documents described above.

Figure 4: Regulatory Responses Related to 14 Milestone Accidents



Note: Other = Action Notices, Final Rules, Letters, Notices, Orders, Plans, Policy Statements, Reports, or Revisions to particular manuals.

Among the 14 milestone accidents, the NTSB found maintenance as a safety issue for seven accidents including the Aloha flight 243 and TWA flight 800. Following Aloha, the FAA published in 1990 the "Aging Aircraft Evaluation Trend Report." A number of changes to regulations were made and many ACs were issued with regard to certification and inspection. Many of the new regulations (as ADs and ACs) were issued after 1998. There may be several reasons why it took 10 years for the FAA to initiate a regulatory response. One is TWA flight 800, which again drew attention to the issue of aging aircraft. The TWA flight 800 Boeing 747-100, manufactured in 1971, was 25 years old with 93,303 flight hours at the time of the accident. Investigation of this accident revealed concern over aging wire bundles as a source of electrical discharge and ignition, and more broadly as a safety concern outside the traditional aging of structural components. In 1998, the FAA issued the "Aging Transport Non-Structural Systems Plan" to address the Gore Commission's recommendations regarding aging aircraft non-structural systems safety issues. Four years later, the FAA published an "interim final rule" mandating age-related inspection and records reviews for multi-engine Part 121, 129 and 135 aircraft which went into effect in December 2003 (Broderick 2003). This interim rule was replaced in January 2005 by the Aging Aircraft Safety Final Rule (Federal Register 2005). According to the FAA, this rule establishes adequate and timely maintenance of age-sensitive parts and components to prevent age-related accidents and extend the airworthy life of the airplanes.

A very important part of the regulatory oversight is the examination of systems and procedures followed in different areas of airline operation and aviation safety. Table 1 shows that almost all the milestone accidents involved a failure or lack of systems and procedures. These accidents included collisions with another aircraft, controlled flight into terrain, or loss of control in flight. Subsequent improvements in systems and procedures should contribute to mitigating the safety risks and reducing the number of these types of accidents. Advanced technology and consideration of human factors are two key approaches for improving systems and procedures that have been pursued in the past few years.

In 1993, the FAA issued the Flight Standard Information Bulletin (FSIB) 93-40A, titled "Human Factors Involved in Inspection and Repair in a Heavy Maintenance Environment." This Bulletin expired in 1994 and was incorporated into Order 8300.10 as Change 10 in the Airworthiness Inspector's Handbook. Two years later, the ValuJet flight 592 accident (1996) prompted a second regulatory response concerning human factors. In 1998, the FAA published, "Human Factors in Aviation Maintenance and Inspection, Strategic Program Plan." In addition to its growing relevance to maintenance and inspection, human factors must also be adequately addressed in design, application of technology, systems, training, and procedures. The U.S. General Accounting Office (1996) issued a report titled, "Human Factors: Status of Efforts to Integrate Research on Human Factors into FAA's Activities." The report highlighted the importance of consistent application of human factors and stated the difficulty in agreeing on how to achieve the goals of human-centered automation.

Technology Response

One of the most significant outcomes, the Aviation Safety Research Act of 1988 (Public Law 100-591), was not a particular technology. This law directed the FAA to be responsible for long-term research, development, and implementation of technological solutions to safety issues raised by aviation accidents. Under this law, the FAA was required to provide an annual report presenting the national aviation research plan for a 15-year period. Interestingly, the law required that the FAA study the relationships between human factors and airline accidents. In addition to the Research Act of 1988, hearings on technological solutions, in general, as well as specific technologies were prevalent throughout the 15 years studied. Hearings were held on technological improvements for aircraft, maintenance and inspection, and air traffic management.

Collision avoidance has received particular attention by the U.S. Congress. Over the 15-year period, 10 hearings examined the issue of collision avoidance and proposed the Traffic Alert and Collision Avoidance System (TCAS) as a solution. TCAS was introduced in 1981 as a vast improvement over earlier solutions. In 1987 Congress passed a law requiring FAA to mandate the use of TCAS (O'Hara 1998). The FAA developed this system and then required airlines to install it at their own cost. To serve the varied needs of the aviation community, three versions of TCAS were developed, each with distinct performance characteristics. TCAS I was for general aviation and small commuters, TCAS II was for commercial aviation, and TCAS III would be a future upgrade for TCAS II (U.S. Congress, Office of Technology Assessment 1989). Public Law 100-223 (1987) required that airlines meet a Dec. 30, 1991, installation deadline for TCAS II, or they would not be permitted to fly in U.S. airspace. Public Law 101-236 (1989-1990), which dealt with Traffic

Alert and Collision Avoidance System for Commercial Aircraft, was promulgated to address, among others, the Northwest Airline flight 1482 (1990) collision-related accident. This public law extended the original deadline for installing this technology on commercial aircraft with 30 seats or more. The collision-related accident involving USAir flight 1493 (1991) further encouraged the requirement for airlines to use TCAS. Full compliance was achieved by the end of 1993 (O'Hara 1998).

In addition to collision avoidance, weather prediction and reporting was another significant safety issue. This concern led to four hearings during the 106th Congressional session (1999-2000) citing the NEXRAD (Next Generation Radar) and Terminal Doppler Weather Radar (TDWR) systems as potential solutions.

Specific technological solutions to address maintenance and aging aircraft include the development of the Fluorescent Penetrate Inspection (FPI) following the uncontained engine failure of United Airlines flight 232 accident. FPI is an inspection technique for surface crack detection in both aircraft and engine components during production, qualification, and in-service assessment (Brasche and Broz 2001). After the TWA flight 800 accident, FAA research intensified and focused on on-board fuel tank inerting. In May 2002, the FAA unveiled a prototype On-Board Inert Gas Generating System (OBIGGS).

Table 2 shows the relationship between select milestone accidents and the specific technological solutions that it contributed to. Table 3 provides a brief description of each of these technologies. The technological contributions were identified by the authors based on review and evaluation of the timeline of actions taken following each accident. Clearly, Northwest Airlines flight 1482 was very significant because it contributed to the development of six different technologies shared between the aircraft and airport operation that address the safety issue of collision.

Many of the milestones accidents accelerated the development or improvement of technologies that enhance aviation safety. Of course, technologies themselves do not prevent accidents from happening. Thus, as advanced technologies were developed and discussed at the policy level, airworthiness directives and advisory circulars were issued by FAA. These directives and circulars are regulatory tools that mandate and guide installation of new technologies and provide proper procedures and training requirements.

While often there are many pressures to address safety deficiencies and accident causes with technological solutions, such solutions have at times created human factors issues such as: man-machine interface, "glass cockpit" approaches, sensory overload, and crew resource management (CRM). An addition of each new piece of equipment or interface requires analysis of human factors. This complicated area of human interface with machines involving human psychology in a very unique environment continues to challenge aviation professionals, policy-makers and regulators.

CONCLUSIONS

This paper describes the process for identifying aviation accidents that have significant impacts on the development of aviation safety in the United States. These accidents are termed milestone accidents. Based on this analysis of the aviation accidents occurring during 1988 to 2002, 14 accidents were considered milestones. These accidents highlight safety issues resulting in a variety of outcomes that characterized the historical record. This paper documents the responses to and outcomes of the milestone accidents and the safety issues raised by these accidents in a complex environment with many layers of interactions. The complex interactions are displayed in the aviation safety timeline. The milestone accidents clearly show that high fatality accidents have a large impact on aviation policy, regulation, and the application of new technology. Fatal accidents, by their inherent seriousness, seem to have the highest impact. However, fatality may be the necessary, but not a sufficient reason for the level of impact an accident may have on changes in policy, regulation and technology. Unique events such as Aloha Airlines flight 243 clearly show that even an accident with few fatalities can lead to Congressional response and regulatory actions. In contrast, fewer hearings and regulatory responses followed the crash of USAir 427 with 132 fatalities.

Table 2: Selected Technology Outcomes Resulting From Milestone Accidents

Accident/ Technology Outcome	ADS-B	AMASS	ASDE-3	AWOS	EVAS	FPI	OBIGGS	ROWS	RVR	TAWS	TCAS II
1989 – United Airlines FL232						✈					
1990 – Northwest Airlines FL1482	✈	✈	✈					✈	✈		✈
1991 – USAir FL1493		✈	✈								✈
1991 – United Airlines FL585				✈							
1995 – American Airlines FL965										✈	
1996 – ValuJet FL592					✈						
1996 – Trans World Airlines FL800							✈				
1997 – Korean Air FL801										✈	
1999 – American Airlines FL1420				✈					✈		

Note: See Table 3 for a brief description of the technologies.

Table 3: Description of Technologies

ADS-B	Automatic Dependent Surveillance Broadcast	Automatically broadcasts aircraft position, altitude, velocity and other data every second to show aircraft's position and altitude on display screens without need for radar
AMASS	Airport Movement Area Safety System	Software enhancement to ASDE-3, provides controller with aural/visual alerts to potential collisions on runway, predicts potential collisions between tracked aircraft and vehicular traffic
ASDE-3	Airport Surface Detection Equipment Model 3	High performance radar scans airport surface to locate positions of aircraft and ground vehicles, displays them for controllers
AWOS	Automated Weather Observing System	Measures, collects and broadcasts weather data to help meteorologists, pilots and flight dispatchers prepare and monitor weather forecasts, plan flight routes, provides necessary information for correct takeoffs, and landings
EVAS	Emergency Vision Assurance System	Displaces all smoke from vision path using Inflatable Vision Unit to provide clear window to critical instruments and flight path through windscreen
FPI	Fluorescent Penetrant Inspection	Inspection technique for surface crack detection in aircraft and engine components during production, qualification, in-service assessment
OBIGGS	On-Board Inert Gas Generating System	Uses aircraft bleed air to generate nitrogen-enriched air to keep oxygen concentration of fuel tank below 12% during flight cycle
ROWS	Runway Obstruction Warning System	Uses sensing loops in pavement to tell controllers when aircraft enter and depart runways and arrive at hold-short lines
RVR	Runway Visual Range	Part of TCAS II, provides a standardized, instantaneous, and accurate method of measuring visibility along runways
TAWS	Terrain Awareness and Warning System	Provides flight crew much earlier aural and visual warning of impending terrain, forward looking capability, and continued operation in the landing configuration
TCAS II	Traffic alert and Collision Avoiding System II	Analyzes projected flight path of approaching aircraft and issues 'Resolution Advisories' to pilot to resolve potential mid-air collisions

Without further analysis of the U.S. Congressional record and resources outside the bounds of this paper, a conclusion cannot be made as to whether significant technological changes are driven by airlines, consumer safety advocates, accident investigations, or industry's recognition of accident precursors. Detailed review of the relevant Congressional documents, including examination of the testimonies, may show that more often there may not be just one plausible explanation for all of the significant technological outcomes. There is no strong evidence pointing to a single factor advancing technological change. Although this research is limited to accidents that occurred in the United States, it is important to address aviation safety issues internationally as well. Examples of the influence of U.S. initiative in aviation having significant impacts internationally are plentiful; including the Family Assistance Act (1996) which showed how U.S. policies and regulations have been responding to changes in civil aviation at the international level, such as the increase of code-share operations.

Future research may apply the selection process to an expanded period. The timeline can particularly benefit from a review of the 10 years immediately following deregulation of the air transport industry in 1978. Inclusion and review of the accidents and safety issues between 1978 and 1988 may reveal correlations between growths in air transport industry after deregulation and the outcomes in the three noted areas.

APPENDIX A
Brief Description of Selected Accidents Including Probable Cause as Determined by the NTSB

***Note: Italicized airline name and flight number = not selected as a milestone accident*

1. 1988 – *American Airlines Flight 132***

On Feb. 3, 1988, a MD-83, N569AA, experienced a spontaneous chemical fire that smoldered out of sight in the cargo hold. On final approach to land, the cabin floor was softening, sinking and simply melting under tremendous heat. Four crewmembers and 9 passengers suffered smoke inhalation or minor injuries. The probable cause was identified as a chemical reaction resulting from a hydrogen peroxide solution, in concentration prohibited for air transportation, which leaked and combined with the sodium orthosilicate-based mixture from an undeclared and improperly prepared container.

2. 1988 – Aloha Airlines Flight 243

On April 28, 1988, a Boeing 737-200, N73711, experienced an explosive decompression and structural failure at 24,000 feet. Approximately 18 feet from the cabin skin and structure aft of the cabin entrance door and above the passenger floor line separated from the airplane during the flight. Of 89 passengers and 6 crewmembers, 7 passengers were seriously injured and 1 flight attendant was killed. The probable cause was identified as failure of the Aloha Airlines maintenance program to detect the presence of significant disbonding and fatigue damage.

3. 1988 – Taca International Airlines, flight number unknown

On May 24, 1988, a Boeing 737-300, N75356, equipped with two CFM56-3-B1 engines, experienced a dual-engine flameout while descending through heavy rain, hail, and turbulence. The crew was unsuccessful in their attempts to restart the engines, and made a successful emergency landing on a levee near New Orleans, Louisiana. No fatalities or injuries. The probable cause was identified as a double engine flameout due to water ingestion which occurred as a result of an in-flight encounter with an area of very heavy rain and hail.

4. 1988 – *Delta Air Lines Flight 1141***

On Aug. 31, 1988, a Boeing 727-232, N473DA, crashed shortly after lifting off from runway 18L at the Dallas-Fort Worth International Airport. Twelve passengers and 2 crewmembers were killed, 21 passengers and 5 crewmembers were seriously injured, and 68 passengers sustained minor or no injuries. The probable cause was identified as takeoff without the wing flaps and slats properly configured.

5. 1989 – United Airlines Flight 811

On Feb. 24, 1989, a Boeing 747-122, N4713U, experienced an explosive decompression as a result of the in-flight loss of the right forward lower lobe cargo compartment door and a part of the right cabin fuselage. Of 337 passengers and 18 crewmembers, 9 occupants were lost during the decompression, and 1 crewmember, 15 flight attendants, and 22 passengers were injured during the decompression and emergency evacuation. The probable cause was identified as the initial failure of the latches at the bottom of the door, explosive decompression and destruction of the cabin and fuselage structure.

6. 1989 – United Airlines Flight 232

On July 19, 1989, a DC-10-10, N1819U, experienced a catastrophic failure of the number two engine during cruise flight and crashed during an attempted landing at Sioux Gateway Airport, Iowa.

One flight attendant and 110 passengers were fatally injured. The probable cause was identified as the uncontained disintegration of the number two engine's fan rotor.

7. 1990 – Avianca Airlines Flight 52

On Jan. 25, 1990, a Boeing 707-321B, with Colombian registration HK2016 crashed in a wooded residential area in Cove Neck, Long Island, New York. Of the 158 persons aboard, 73 were fatally injured. The probable cause was identified as the failure of the flight crew to adequately manage the airplane's fuel load, and their failure to communicate an emergency fuel situation to air traffic control before fuel exhaustion occurred.

8. 1990 – Northwest Airlines Flight 1482

On Dec. 3, 1990, a McDonnell Douglas DC-9, N3313L, collided with Northwest Airlines Flight 299, a Boeing 727 near the intersection of runways 09/27 and 03C21C at Detroit Metropolitan/Wayne County Airport. Of the 40 passengers and 4 crewmembers on board, 7 passengers and 1 crewmember were killed. The probable cause was identified as the lack of proper crew coordination by the DC-9, as well as deficiencies in ATC services, surface marking and cockpit resource management.

9. 1991 – USAir Flight 1493

On Feb. 1, 1991, a Boeing 737-300, N388US, collided with Skywest Flight 5569, a Fairchild Metroliner, while landing on runway 24L at Los Angeles International Airport, California. All 10 passengers and 2 crewmembers aboard the Metroliner and 20 passengers and 2 crewmembers aboard B-737 were fatally injured. The probable cause was identified as the failure of the Los Angeles Air Traffic Facility Management to implement procedures that provided redundancy comparable to the requirements contained in the National Operational Position Standards and the failure of the FAA Air Traffic Services to provide adequate policy direction and oversight to its ATC facility managers.

10. 1991 – United Airlines Flight 585

On March 3, 1991, a Boeing 737-291, N999UA, crashed while maneuvering to land at Colorado Springs Municipal Airport, Colorado. The airplane was destroyed by impact force and fire; all 25 persons onboard were killed. The probable cause was identified as un-commanded rudder deflection.

11. 1994 – USAir Flight 427

On Sept. 8, 1994, a Boeing 737-3B7, N513AU, crashed while maneuvering to land at Pittsburgh International Airport, Pennsylvania. All 132 persons on board were killed. The probable cause was identified as a loss of control of the airplane resulting from the movement of the rudder surface to its blow down limit. The rudder surface most likely deflected in a direction opposite to that commanded by the pilots as a result of a jam of the main rudder power control unit servo valve secondary slide to the servo valve housing offset from its neutral position and over travel of the primary slide.

12. 1995 – American Airlines Flight 1572

On Nov. 12, 1995, a McDonnell Douglas MD-83, N566AA, was substantially damaged when it impacted trees in East Granby, Connecticut. The airplane also impacted an instrument landing system antenna at its landed short of the runway on grassy, even terrain. No fatalities occurred. The probable cause was identified as the flight crew's failure to maintain the required minimum descent altitude until the required visual references identifiable with the runway were in sight.

13. 1995 – American Airlines Flight 965

On Dec. 20, 1995, a Boeing 757-223, N651AA, struck trees and then crashed into the side of a mountain near Buga, Colombia, in night visual meteorological conditions, while descending into the Cali area. The airplane was destroyed, and all but four of the 163 passengers and crew onboard were killed. The probable cause was identified by the Civil Aviation Authority of Colombia as the flight crew's failure to adequately plan and execute the approach to runway 19 at SKCL; failure of the flight crew to discontinue the approach into Cali; the lack of situational awareness of the flight crew regarding vertical navigation; failure of the flight crew to revert to basic radio navigation at the time when the FMS (Flight Management System)-assisted navigation became confusing and demanded an excessive workload in a critical phase of the flight.

14. 1996 – ValuJet Flight 592

On May 11, 1996, a McDonnell Douglas DC-9-32, N904VJ, crashed into the Everglades swamp shortly after takeoff from Miami International Airport, Florida. All 110 persons aboard were killed. The probable cause was identified as improperly packed oxygen generators. The generators ignited, leading to a fire, which burned through control cables and filled the cabin with smoke.

15. 1996 – TWA Flight 800

On July 17, 1996, a Boeing 747-131, N93119, crashed into Atlantic Ocean about 8 miles south of East Moriches, New York, after taking off from John F. Kennedy International Airport, New York. All 230 people on board were killed. The probable cause was identified as the explosion of the center fuel tank.

16. 1997 – Korean Air Flight 801

On Aug. 6, 1997, a Boeing 747-3B5B, with Korean registration HL7468 crashed at Nimitz Hill, Guam. Of the 254 persons on board, 228 were killed; 23 passengers and 3 flight attendants survived the accident with serious injuries. The probable causes were identified as the captain's failure to adequately brief and execute the non-precision approach and the first officer's and flight engineer's failure to effectively monitor and cross-check the captain's execution of the approach.

17. 1999 – American Airlines Flight 1420

On June 1, 1999, a McDonnell Douglas DC-9-82, N215AA, crashed after it overran the end of runway 4R during landing at Little Rock National Airport, Arkansas. Of the 145 people on board, the captain and 10 passengers were killed; the first officer, the flight attendants, and 105 passengers received serious or minor injuries; and 24 passengers were not injured. The probable cause was identified as the flight crew's failure to discontinue the approach when severe thunderstorms and their associated hazards to flight operations had moved into the airport area and the flight crew's failure to ensure that the spoilers had extended after touchdown.

18. 2000 – Alaska Airlines Flight 261

On Jan. 31, 2000, a McDonnell Douglas MD-83, N963AS, crashed into the Pacific Ocean about 2.7 miles north of Anacapa Island, California. The 2 pilots, 3 cabin crewmembers, and 83 passengers on board were killed. The probable cause was identified as a loss of airplane pitch control resulting from the in-flight failure of the horizontal stabilizer trim system jackscrew assembly's acme nut threads.

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