
ANOTHER APPROACH TO ENHANCE AIRLINE SAFETY: USING MANAGEMENT SAFETY TOOLS

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ABSTRACT

The ultimate goal of conducting an accident investigation is to prevent similar accidents from happening again and to make operations safer system-wide. Based on the findings extracted from the investigation, the "lesson learned" becomes a genuine part of the safety database making risk management available to safety analysts. The airline industry is no exception. In the US, the FAA has advocated the usage of the System Safety concept in enhancing safety since 2000. Yet, in today's usage of System Safety, the airline industry mainly focuses on risk management, which is a reactive process of the System Safety discipline. In order to extend the merit of System Safety and to prevent accidents beforehand, a specific System Safety tool needs to be applied; so a model of hazard prediction can be formed. To do so, the authors initiated this study by reviewing 189 final accident reports from the National Transportation Safety Board (NTSB) covering FAR Part 121 scheduled operations. The discovered accident causes (direct hazards) were categorized into 10 groups— Flight Operations, Ground Crew, Turbulence, Maintenance, Foreign Object Damage (FOD), Flight Attendant, Air Traffic Control, Manufacturer, Passenger, and Federal Aviation Administration. These direct hazards were associated with 36 root factors prepared for an error-elimination model using Fault Tree Analysis (FTA), a leading tool for System Safety experts. An FTA block-diagram model was created, followed by a probability simulation of accidents. Five case studies and reports were provided in order to fully demonstrate the usefulness of System Safety tools in promoting airline safety.

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INTRODUCTION

Regardless of the slow recovery of passenger volume, the air transportation industry is steadily regaining its customers (Woodyard, 2004). For example, in the Asia-Pacific region, the outbreak of Severe Acute Respiratory Syndrome (SARS) between 2002 and 2003 had discouraged passengers from traveling with airlines and substantially consumed airline profits. Asian passengers are now gradually rebuilding their confidence in air transportation because of the relief of possible pathological contagions (Dennis, 2003; FAA, 2004; Lu, 2003). In the United States (U.S.), after the disastrous September 11, 2001 (9/11) terrorist attacks resulting in a massive economic loss (Archibold, 2001; Eisenberg, 2001; Kluger, 2001), public confidence in air transportation is recovering due to the government's implementation of advanced technologies and necessary means to ensure aviation safety and airport security (Loy, 2003 July).

Historically, the U.S. Federal Aviation Administration (FAA) is responsible for fostering and encouraging civil air commerce and simultaneously auditing aviation safety (Adamski & Doyle, 1999; Rollo, 2000; Wells, 1999). However, the FAA's "dual-mandate" responsibility has resulted in criticism in terms of the lack of a sufficient ability to accomplish safety surveillance (Carlisle, 2001; Carmody, 2001; Donnelly, 2001; Filler, 2001; Nader & Smith, 1994; Stout, 1999). Not surprisingly after 9/11, the FAA's workload was immediately increased due to the urgent response to *war on terror*. In order not to overburden the FAA, the Transportation Security Administration, initially a new branch of the Department of Transportation and now attached to the Department of Homeland Security, was specifically created to take charge of the overall transportation safety. However, despite a tightened airport security, aircraft accidents that endanger aviation passengers still occur periodically (e.g., the crash of American Airlines Flight 587 in New York on November 11, 2003 and US Airways Flight 5481 in Charlotte, NC, on January 8, 2003). Accidents indicate a continuing demand to improve safety; but at the same time, most airlines operate with a "red-ink" balance sheet (Lu, 2003). In fact, the

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airline industry is faced with a critical challenge: improving safety in an expense-reducing environment. In this situation, a practical model that assists safety managers in promptly identifying safety deficiencies would be very helpful.

LITERATURE REVIEW

Although the airline industry is extremely safe, finding a better way to continuously audit and promote aviation safety is a perpetual duty for all safety enthusiasts. During the past decade, several leading media reports—the *Wall Street Journal* (Dahl & Miller, 1996; Goetz, 1998) and *USA Today* (Stroller, 2000)—have tried to rank airline safety by solely focusing on a single element: the accident rate. In addition to the reports from Dahl and Miller, Goetz, and Stroller, Bowen and Lu (2000) advocated the importance of measuring airline safety performance and suggested a more comprehensive tool. As advocated by Bowen and Lu in 2000, a more real-time risk-audit model available for airline managers and government agencies could promptly help remedy potential threats to safety. In 2001, Bowen and Lu initiated a new safety measuring mechanism—the Aviation Safety Rating. This study compared 10 major airlines' safety performance based on four essential categories— Enforcement Action, Accident Rate, Management Performance, and Financial Health— with 17 selected safety factors (Bowen & Lu, 2001). By applying Analytic Hierarchy Process as well as the national Airline Quality Rating, a relative comparison of safety performance among 10 US-based airlines was generated. The ASR provided a reference table of the airline overall safety that was available for the flying public and government agencies. In order to help airline managers prioritize the accident factors for effective safety training, Bowen and Lu (2004) conducted a follow-up study focusing on the *criticality* of selected risk factors affecting overall airline safety. They reported “the level of importance” pertaining to the selected safety factors using a new terminology, namely performance sensitivity (Sp). They defined Sp as: *the percentage change of overall safety score due to the percentage change of a specific safety factor*. Based on Sp calculation, a list of prioritized factors impacting safety performance was created. The result showed that fatality rate, average fleet age, and accident rate were the three most critical factors affecting an airline's overall safety performance (Bowen & Lu, 2004a).

Although the prior studies have proposed tools for measuring airline safety performance, they all had one thing in common: they did not discover the genuine cause of accidents. Further research is required so as to reveal the causality between root factors, causes, and accidents. This situation opens a window for further research. With the discovery of root factors leading to causes of accidents, a model that targets on accident prevention

and safety training could be formulated. In this study, the System Safety techniques were applied in an attempt to fill this knowledge gap.

The System Safety concept

System Safety was conceptualized by the U.S. aerospace industry in the late 1940s (Vincoli, 1993). Traditionally, System Safety experts in aerospace engineering applied systemic analysis to identify operational hazards and subsequently provide countermeasures before a mishap in order to eliminate potential risks or hazards (Malasky, 1982; Roland, & Moriarty, 1990). System Safety is defined by Military Standard 882B as “the application of engineering and management principles, criteria, and techniques to optimize safety within the constraints of operational effectiveness, time, and cost throughout all phases of the system life cycle” (Layton, 1989, p.1). It is widely known that using System Safety concepts is an effective approach to reduce risk by identifying potential hazards, providing countermeasures, and assessing the outcome in relation to an operational system (Malasky, 1982; Roland, & Moriarty, 1990; Vincoli, 1993). As noted by Vincoli, a countermeasure could be in the format of system re-modification, warning device, safety training, or regulatory change; and the application of a specific countermeasure is based on the result of cost-effect analysis.

Risk matrix and risk chart

System Safety is a doctrine used to minimize risk, optimize safety, and maximize system’s expected function (Layton, 1989; Malasky, 1982, Vincoli, 1993) by using a “risk matrix” (see Appendix A). In the “Risk Matrix”, risk is defined as the “likelihood or possibility of hazard consequences in terms of severity and probability” (Vincoli, 1993, p.10). To further explain this concept, if either the probability (the likelihood of a condition or a set of conditions that exist in a given environment) or severity (the description of hazard level based on real or perceived potential for causing harm, injury, or damage) or both can be minimized, the risk (R) of an accident will be minimized consequently. Thus, when the reduction of a potential risk (R) becomes urgent, the multiplication of probability (P) and severity (S) (i.e., Risk = Probability x Severity) can be flexibly used to achieve the determined safety goal (Malasky, 1982; Roland, & Moriarty, 1990; Vincoli, 1993). To do so, a Risk Chart (see Appendix B) should be designed to better interpret the meaning of the original risk matrix in the hope of shifting the line of R_3 to R_2 or even R_1 (i.e., either Probability/Frequency is reduced from “A: Frequent” toward “E: Impossible” or Severity is compressed from “I: Catastrophic” toward “VI: Negligible”).

The application of System Safety concept

There are very few studies using System Safety in promoting aviation safety regardless of the common application in the fields of aerospace engineering, product manufacturing and design, environmental hygiene, and medicine.

In the medical safety field, Robert L. Helreich (2000) advocated the application of the System Safety error management concept in medical practice. In his study, he first determined the origin of System Safety stemming from aerospace engineering and then the usefulness of data management pertained to hazard reduction. To accomplish hazard reduction, a well-managed database was the key to prevent medical malpractices based on the statistical predication of the likelihood of a failure. Yet, solely addressing the quantitative forecast, Helreich's study did not provide any workable models or procedures that the industry could adopt and implement. In fact, Helreich's work was not the only application of System Safety techniques in medical industry. Manon Crohecke and his research associates (1999) and William Hyman (2002) utilized the leading tool of System Safety, the well-known FTA, in evaluating potential hazards associated with new innovated medical devices before moving toward the production phase within the device's life cycle.

In aviation safety, the military launched System Safety techniques to improve pilot training procedures. According to Diehl's (1991) cross-referenced analysis of 208 military accidents, the top three pilot errors leading to mishaps were decision making, mission analysis, and situational awareness. Human error was found to be the major cause of aircraft accidents in the U.S. Air Force (Diehl, 1991). He discovered that the breakdown of cockpit communication/team performance, known as crew coordination, had directly constituted military aircraft mishaps. As a result, a mandatory crew and cockpit resource management (CRM) training, developed by National Aeronautics and Space Administration (NASA), for military aircrews was immediately put in place. Diehl's study also used System Safety techniques to suggest a modification of the cockpit layout of the Cessna Citation used by U.S. Air Force officers. He conducted a hazardous and ergonomic analysis and suggested that the cockpit control panel should be redesigned in order to eliminate possible confusions between pilots and their working environment. His study linked System Safety analysis, accident investigation, and hazard identification, to human factor and CRM training. He subsequently recommended the development of a user-friendly cockpit for military pilots.

A recent study by Thom and Clariett (2004) was published in Collegiate Aviation Review focusing on the applicability of job safety and task analysis, another essential tool of System Safety. In their study, a basic concern of System Safety analysis, namely job safety analysis, was closely

interpreted and the layout of human-machine interface was emphasized. Using the Risk Homeostasis Theory of human behavior, their study helped identify potential hazards surrounding the hangar, factory, or student workshop both internally and externally (Thom & Clariett, 2004). This study was of great interest to the aviation community. This study introduced aviation educators to the heart of System Safety techniques (job safety, environmental factors, failure modes, human error, and hazardous categories) and developed significant interest in it within the aviation community.

The previous studies showed the importance and applicability of aerospace engineering's System Safety techniques in promoting military flight safety, reducing medical service fault and malpractice, enhancing cockpit design, and identifying workplace hazards. Although System Safety has been recognized by various industries in upgrading safety or reliability, only a small portion of the aviation research community have utilized specific System Safety tools to promote airline safety.

The FAA's System Safety efforts

The Office of System Safety is the leading player in the FAA's work on aviation System Safety research. It was in 2000 that the FAA Office of System Safety first introduced System Safety concept to the aviation industry and initiated risk management workshops for its own staffers in Hampton, Virginia as a compliance activity after the FAA Order 8040-4 was published (FAA, 1998). The FAA Order 8040-4 required the Office of System Safety to incorporate a risk management process for all high-consequence decisions (FAA, 1998, p.1) and to provide a handbook/manual of System Risk Management and to recommend "tools" of System Safety to all US-based airlines. In addition, an annual System Safety conference and workshop available for airline managers has become routine since 2000. The research efforts from the FAA, project contractors and other sources were discussed and ideas were exchanged during each conference or workshop. Despite the handbook of System Safety containing essential System Safety theories, the current System Safety publications are limited to engineering design; navigation system; weather and turbulence forecast; global positioning systems; runway incursion; consumer safety guidelines; and airport operational procedures. On the other hand, the usage of System Safety has been closely tied to data collection and risk management on a voluntary basis in the airline industry. Examples of such data collection and management include the Air Transportation Oversight System (ATOS), FAA Safety Reporting System and Database (SRSD), NASA Aviation Safety Reporting System (ASRS), Flight Operational Quality Assurance (FOQA), Air Carrier Operations System Model (ACOSM), and American and Delta Airlines' Aviation Safety Action Program (ASAP) (see Appendix

C). It is obvious that most current studies from the airline industry have been limited to a basic introduction of System Safety management, data collection for risk analysis and trend study such as SRSD, ASAP, ASRS, or FOQA. Applying System Safety “tools” such as Fault Tree Analysis (FTA) to identify and prioritize hazardous precedents upstream, determine countermeasures, reduce hazardous probability or severity, and prevent accidents upfront throughout the life cycle of flight operation would provide another meaningful mechanism to the aviation community. It would also extend the scope of the usage of System Safety. In this paper, one of the essential System Safety tools, namely FTA, was adopted for the required calculation of hazardous probability and future simulations purpose.

Fault tree analysis

FTA is used to examine an extremely complex system involving various targets such as skills, quality, equipment, facility, operators, finance, management, reputation, or property within the domain of operation (Malasky, 1982).

“By placing each contributing factor in its respective location on the tree, the investigator can accurately identify where any breakdowns in a system occurred, what relationship exists between the events, and what interface occurred.” (Vincoli, 1993, p.135)

FTA uses an inductive approach in conjunction with Boolean logic and failure probability that connects a series of events leading to the top-event (Roland & Moriarty, 1990; Vincoli, 1993) (see Appendix D). To accomplish a holistic view of an aviation system facing critical hazards, FTA tracks upstream and identifies causal factors that may lead to an accident or system failure (Brown, 1976). In addition, FTA will help researchers build an advisory foundation (recommendation-basis) for developing a better accident prevention program from the bottom-up (Brown, 1976; Malasky, 1982). The basic procedure of conducting FTA is suggested as follows: 1) identifying the top-event, 2) finding all contributory events from top-down, and 3) creating a full “fault tree” for analysis and recommendation (Roland & Moriarty, 1990; Vincoli, 1993). Because FTA may encompass hundreds of root factors underpinning accident causes, this study introduced a mini-FTA model that is sufficient to describe its purpose of accident-prevention and safety training (Vincoli, 1993).

Research focus

In order to fulfill knowledge gap and further apply System Safety in promoting airlines' operational safety, the implementation of this study was designed with the following four stages: 1) identifying the direct hazards leading to airline accidents, 2) discovering critical safety factors constituting the causes leading to an accident, 3) creating an accident prevention model using FTA for risk simulation, and 4) providing case studies and reports showing the applicability of FTA in commercial aviation safety by recommending training emphasis.

RESEARCH TECHNIQUES**Document review**

Accident reports (between 1999 January and 2004 May) were retrieved from the U.S. NTSB Accident Docket Databases focusing on FAA FAR Part 121 scheduled U.S. air carrier services. Accident reports were limited to final reports meaning the accident investigation had been completed before the day of data retrieval and analysis of this study.

Data coding

Data coding is a systematic procedure for synthesizing the significant meanings of texts by references and comparisons across different records and coders (Maxwell, 1998; Miles & Jman, 1994). Data coding is a standard practice for a qualitative study (Gough & Scott, 2000). Based on the aforementioned analytical highlights of data coding, this study coded accident reports based on eight (8) main components: (a) name of air carrier, (b) date of accident, (c) aircraft type, (d) number of fatalities, (e) number of injuries (both serious and minor), (f) aircraft and property damage, (g) cause or causes of an accident, and (h) factor or factors of an accident cause or causes.

Reliability and validity

The reliability of this project rests in the category of research consistency. This consistency involved operational processes of Delphi techniques (re-identification) and the conformability of results (Creswell, 1998; Maxwell, 1994). This study used cross-references skill of qualitative data coding (QDA) double-checking two codebooks obtained from different analytical time and researchers (August 10 and October 1). The obtained reliability rate was 90.9% (ten out of eleven causes were concurred where the code of "Weather" was not identified by one of the researchers initially). After a third round of data review, the cause labeled as "Weather" was collectively updated and placed into the cause labeled "Turbulence." This

agreement was done after the initial reliability rate (90.9%) was achieved. About validity, the governmental information databases help researchers secure data validity of a qualitative research based on the value of verification, trustworthiness, and authenticity (Creswell, 1998). With this in mind, the NTSB accident reports satisfy the validity criteria of good qualitative research (Berg & Latin, 1994; Creswell, 1998; Lincoln & Guba, 1985).

FINDINGS

The time-period of data retrieval and analysis was between June 18 and December 11, 2004. There were a total of 189 final accident reports available on the NTSB Aviation Accident Database dated between January 1, 1999 and May 31, 2004. The finding sections were reported as follows: 1) The causes of airline accidents, 2) The contributing factors of accident causes, 3) FTA model and probability simulation, and 4) Case studies and FTA reports.

The direct causes of airline accidents

The direct causes leading to FAR Part 121 airline accidents between January 1999 and May 2004 were ranked and categorized as follows (see Table 1):

Table 1. The Direct Causes of FAR Part 121 Airline Accidents

Rank	Accident Cause*	Number of Cases	% of Cases
1	Flight Operations	46	24.34%
2	Ground Crew	43	22.75%
3	Turbulence	40	21.16%
4	Maintenance	25	13.23%
5	Foreign Object Damage (FOD)	15	7.99%
6	Flight Attendant	8	4.23%
7	Air Traffic Control (ATC)	4	2.12%
8	Manufacturer	4	2.12%
9	Passenger	3	1.59%
10	FAA	1	0.53%

* Please see Appendix E for the definition of each accident cause after data coding

The accident cause due to *Flight Operations* error resulted in 46 accidents (24.34%), which was the most critical individual cause of the Part 121 accidents. There were 43 accidents as a result of *Ground Crew* error

followed by *Turbulence* (40 cases), *Maintenance* (25 cases), *FOD* (15 cases), *Flight Attendant* (8 cases), *ATC* (4 cases), *Manufacturer* (4 cases), *Passenger* (3 cases), and *the FAA* (1 case). Although *Flight Operations* error was the most significant cause (24.34%), the dyad of *Ground Crew* and *Maintenance* (non-flight) error had resulted in 68 accidents (35.98% of the overall mishaps).

The contributing factors of accident causes

The factors leading to *Flight Operations* error were: 1) loss of situational awareness, 2) misjudgment (ground clearance), 3) weather (contaminated, snowy, or icy runway), 4) ineffective communication, 5) operational deficiency (supervision, misjudgment, preflight inspection), or lack of training (heavy landing, go-around procedure, unfamiliar with regulations, and decision-making), 6) non-compliance with standard operational procedures, 7) over-reaction (evasive maneuvers, abrupt reaction to Traffic Collision Avoid System warning), 8) physical fatigue, 9) weather and airport information ignorance (weather briefing, turbulence report, Notice to Airmen, Minimum Equipment List, outdated Runway Visual Range).

The factors leading to *Ground Crew* error were: 1) poor situational awareness (clearance, airstair/jet bridge/vehicle operations), 2) ineffective communication (tug/truck/beltloader driver-pilots-wing walkers), 3) lack of supervision/quality assurance, 4) ramp agents' ignorance of safety criteria, 5) physical fatigue, and 6) personal health and medication.

Most accidents due to *Turbulence* resulted in flight attendant injuries. The factors that led to injuries or fatalities resulting in the cause of turbulence were: 1) lack of weather awareness (pilots or dispatchers' poor discipline pertaining to weather evaluation), 2) inadequate training of cabin crews when encountering turbulence (inaccurate cabin reaction procedures, ineffective crew communication, delayed public announcement), and 3) passengers' inability of cooperating with cabin crews during emergency situation.

The factors that led to *Maintenance* error (equipment contamination, corrosion, engine failure, etc.) were: 1) the lack of quality assurance and supervision on performance, 2) non-compliance of standard maintenance procedures (SMPs), 3) incorrect data from the FAA, 4) lack of training and knowledge, 5) rushed service, and 6) operational ignorance.

The factors that led to *FOD* cases were: bird/geese strikes and collision with deer. The FOD frequently occurred during: 1) take-off and landing phase and 2) night flights around remote non-hub airports. The factors leading to the cause of *Flight Attendant's* mistakes were: 1) unfamiliarity with safety procedures during evacuation, 2) poor communication (between pilot, flight attendants, or ramp/gate agents), and 3) inadequate training with

abnormal emergency conditions. The factors that led to the cause of *ATC* error were: 1) improper ATC service (the result was pilot's abrupt maneuver) and 2) a failure to provide adequate in-flight separation.

The factors contributing *Manufacturers'* error were: 1) inadequate manual information (e.g., gearbox maintenance manual), and 2) improper material and imperfect design. The factors that led to the cause of *Passengers* and their injuries were: 1) passengers' non-compliance with regulations during emergency situation, and 2) unruly passengers and behaviors. The one factor leading to the cause of *FAA* was the FAA's improper issuance of airworthiness certificate and Airworthiness Directives for specific parts.

FTA model and probability simulation

The findings revealed that there were 10 main causes, along with 36 associated root factors, which led to airline accidents during this time period. A mini-FTA block diagram showed in Appendix F presents an inductive relationship among accidents (top level event), the accident causes (second level events) and the causes' root factors (the lowest level events) (see Appendix F). Each accident cause contained from one to nine contributory root factors. Based on the Boolean logics, "AND" and "OR" gates, researchers are able to examine the whole system from the bottom to the top level. These root factors (the lowest level events) included inadequate flight performance, fatigue, poor quality assurance, carelessness, air-rage, lack of situation awareness, non-compliance with SOPs, miscommunication, etc. The mini-FTA model in Appendix F also demonstrates an individual root factor could create a category of accident cause (second level event) that eventually leads to an accident (top level event).

To address the criticality of the 36 discovered root factors that led to the accidents, simulating accident probability of the top-event would help explain the significance of the FTA model and predict the likelihood of the top level event. For instance, using the study of Bowen and Lu's assessment of major airlines' safety performance in 2001 and 2004, the probability of pilot fatigue (a root factor) leading to an accident was about 1.7×10^{-5} (1.7 cases per one hundred thousand flights) (Bowen and Lu, 2004). Because there could be hundreds of different factors associated with one accident cause, the probability for an accident cause to exist would be $(1.7 \times 10^{-5}) \times 100$, which is 1.7×10^{-3} (see Appendix G). And since any of the ten accident causes (an "OR" gate logic in this study) could lead to the top-event, the probability for an accident to occur could be $(1.7 \times 10^{-3}) \times 10$, which is 1.7×10^{-2} meaning 1.7 accidents for every 100 flights. This high probability of an accident should have drawn the attention of the aviation community.

Reversely, based on the same FTA model presented in Appendix G, if airlines can reduce the accident probability of each root factor to 1.7×10^{-7} instead of 1.7×10^{-5} (as a result of imposing safety trainings, new safety guidelines, effective flight training, or upgraded navigation technologies), the ultimate accident probability of the top level event becomes 1.7×10^{-4} meaning 1.7 mishaps for every 10,000 flights. This simulation of accident probability shows that it is extremely critical for the airlines to mitigate potential hazards from the bottom level as early as possible. If the probability of each root factor (the lowest level of the fault tree) could be compressed or even eliminated, the probability of accident causes (the second level of the fault tree) resulting from a combination of various root factors would be dramatically reduced. Eventually, the probability for the top level event (i.e., an accident) to occur could be minimized.

Case studies and FTA reports

The main purpose of conducting FTA in aviation safety is to identify potential hazards, provide recommendations and reports, and to prevent similar accidents from happening again. In order to further strengthen the applicability of the FTA accident model, case studies are provided. All cases were retrieved from the NTSB Accident Database online either in a PDF version.

Case 1. NTSB ID: LAX00LA223

An engine forward cowling door on the number 1 engine separated from the engine nacelle during the take off rolling at Las Vegas International Airport. The separated part consequently struck the horizontal stabilizer attached to the vertical fin. The pilot described that aircraft vibrated on runway during the take off rolling. The aircraft was under an RON (Remain Over Night) check due to the complexity of maintenance. The technicians opened the engine cowling door for the needed RON check at night but failed to ensure the proper hand-over procedure with the day-shift team the next morning. In addition to the required follow-up in relation to engine inspection, the day-shift team was assigned with other inspection tasks as well (NTSB, 2001, August 21)

The cause and root factor of this accident was mechanic's failure to refasten the cowling door prior to signing off the aircraft back to service. Providing countermeasures should focus on retraining communication skills and quality assurance and re-emphasizing team work capability based on the recommendations of AC-120-51D and maintenance resource management (MRM).

Case 2. NTSB ID: NYC02LA013

Before the landing, the captain briefed a “no go-around” for a night visual approach even though the approach was not stabilized. The airspeed was decreasing to near the speed of stall. After touch down, the aircraft maneuvered at a nose-high pitch attitude and struck the runway on the aft fuselage. The first officer did make an initial callout about the stall airspeed but the captain did not respond. During the post-accident interview, the captain reported that she decided to land without initiating go-around because there was no traffic on the runway at night. The first officer did not challenge the captain even though the decision was wrong. The captain described that the first officer was very quiet; yet the first officer complained that the captain was self-defensive and did not like any criticisms (NTSB, 2003a)

The cause of this accident was the captain’s failure to maintain airspeed resulting in both a stall and a hard landing. The factors involved were the failure of both pilots to comply with the company’s CRM guidelines, flight manual procedures, and the captain’s improper approach briefing.

Providing countermeasures should focus on: (a) recurrent CRM training, (b) pilot’s flight procedure retraining, and (c) flight operation proficiency and training guidelines should come from AC-120-51D, Preflight SOPs, and airline’s simulator training procedures.

Case 3. NTSB ID: DCA99MA060

A McDonnell Douglas DC-9-82 (MD-82) crashed after it overran the end of runway 4R during landing ... After departing the end of the runway, the airplane failed to maintain vertical airspeed and struck several tubes extending outward from the left edge of the instrument landing system (ILS) localizer array...The airplane was destroyed by impact forces and a post-crash fire (NTSB, 2003b, p. 169-170).

The cause and root factors of this accident were “The flight crew’s failure to discontinue the approach” and their failure to ensure the spoilers’ extension for landing due to (a) flight crew’s fatigue and stress, (b) situational awareness of airport weather, and (c) incorrect operation of using reverse thrust after landing. Providing countermeasures should focus on conducting recurrent CRM trainings for pilots and retraining pre and post landing procedures based on the recommendations of AC-120-51D and SOPS of flight operations.

Case 4. NTSB ID: DCA03MA022

A Raytheon (Beechcraft) 1900D crashed shortly after takeoff from runway 18R at Charlotte-Douglas International Airport due to the airplane's loss of pitch control during take-off. The 2 flight crewmembers and 19 passengers aboard the airplane were killed, 1 person on the ground received minor injuries (NTSB, 2004a, p. 13)

The cause and root factors of this accident was the loss of pitch control resulted from an incorrect rigging of the elevator system compounded by the airplane's aft center of gravity, which was substantially out of limit. Additional contributing factors to the cause of incorrect rigging were: (a) lack of oversight of the maintenance station by the airline and the FAA; (b) improper maintenance procedures and documentation; (c) erroneous weight and balance calculation; (d) ineffective manufacturer's onsite quality assurance; and (e) the FAA's outdated weight and balance assumptions.

Providing countermeasures should focus on: (a) revising the FAA's weight-and-balance reference data, (b) imposing recurrent trainings for quality assurance (QA) inspectors both for airline and manufacturer, (c) providing aircraft technician's job compliance training, and (d) ensuring preflight SOPs based on the FAA's formed rulemaking procedures and inspection handbooks, maintenance trouble-shooting SOPs, preflight SOPs, maintenance resource management (MRM) guidelines, and AC-120-51D recommendations.

Case 5. NTSB ID: NYC03FA039

A Boeing 757 was struck by a taxiing Airbus, while parking at the gate with passengers aboard. Maintenance technicians were taxiing the Airbus. The maintenance technicians testified that both parking brakes were activated while waiting for ground crews to arrive for the follow-up procedures. He released the parking brake after the ground crews arrived and took over the residual operation. The technicians slightly increased the throttles because the aircraft did not move after parking breaks were released. The airplane struck the jet way despite the engine throttles were repositioned to idle speed (NTSB, 2004b)

The cause and root factors of this accident are the aircraft technician's lack of training in terms of aircraft system, maintenance procedures, and ground safety guidelines. Providing countermeasures should focus on: (a) imposing a recurrent training of maintenance standard operation procedures (SOPs), (b) aircraft system training, and (c) ground operation safety training based on the maintenance resource management (MRM) guidelines, AC-120-51D recommendations, and manufacturer's system handbooks or maintenance manuals.

CONCLUSION

This study discovered the 10 direct causes leading to accidents and 36 root factors behind accident causes. By using FTA, aviation safety practitioners can design a more efficient and effective safety training aiming to detect risk factors, provide countermeasures, and reduce the associated hazardous probability and severity. This study is concluded as follows:

1. Implementing System Safety techniques is feasible. In this study, the ultimate goal of conducting System Safety analysis using FTA is to prevent future accidents by identifying potential hazards and providing countermeasures and recommendations. Although many studies had been accomplished measuring the overall safety performance (Bowen & Lu, 2001 & 2004a; Dahl & Miller, 1996; Goetz, 1998; Stroller, 2000), they did not provide a good model for safety practitioners to promptly and effectively identify accident causes and their root factors. Without identifying specific root factors and accident causes leading to mishaps, solely measuring safety performance could be of limited value and result in aimless and ineffective safety training. In fact, System Safety experts advocate four fundamental levels of safety precedence regarding hazard ramification. They are reengineering; redundant system design; warning signals and devices; and safety training and education. The most inexpensive safety precedence is safety training and education (Vincoli, 1993). This is an important feature for today's airline businesses suffering from financial hardships and simultaneously concerned with offering the highest degree of care in terms of passenger's safety.

2. Fault Tree Analysis (FTA) is plausible. It is important to understand FTA because it helps safety enthusiasts (government or airlines) to effectively and promptly isolate accident postulates and to implement strategic safety prevention programs from the bottom-up. Based on the FTA block-diagram in this study, any of the root factors on the bottom level can form a *cut-set*, that is, a chain-of-events that can result in an accident or a system failure, breaking down the entire system. Hence, compressing or eliminating the failure probability of root factors from the lowest level of "the tree" should be regarded as the training priority.

3. Human Factors training is critical to pilots. Regardless of the accident cause of turbulence and FOD, "pilot error" was the primary factor leading to airline accidents in this study. Krause (1996) and Orlady (1999) stated that Human Factors is a very powerful training tool for pursuing an error-free and safety-laden airline operation. Since 1990, the FAA has regulated CRM training for flight crews (based on NASA's Human Factors research in the early 1970s). This can be found in Federal Aviation Regulation (FAR) Part 121 Subpart N for major air carriers and for Part 135

regional commuters under SFAR 71 (Aviation Supplies & Academics [ASA], 2001).

4. Non-flight activities are equally hazardous as flight activities. According to the findings of this study, non-flight error constituted more mishaps (68 cases) than flight operation (46 cases). In fact, the aviation safety net consists of flight crews, maintenance personnel, air traffic controllers, airplane dispatchers, flight attendants, ramp agents, airport security, and all related professionals. Aviation personnel should work closely together because a single flawed portion of the safety net could result in an unrecoverable safety breakdown and, thereby, human injuries, fatalities, or substantial financial loss. By virtue of the *Swiss-cheese* safety model, aviation accidents happen when unsafe acts or operations are present and line up simultaneously (Reason, 1990; Wood, 1997). With this in mind, in order to strengthen the aviation safety net based on mini-FTA model, it may be reasonable for the aviation community to support a mandatory Human Factors or MRM training for ground and maintenance personnel.

COMMENTS

Although the potential cost is always a big concern regarding an accident prevention program (Del Valle, 1997; Duke, 1999; Finder, 1999; Hahn, 1997; Morris, 2001; Morris, Rigavan, Whitelaw, Glasser, Strobel, & Eltahawy, 1999; Wald, 2000), providing safety trainings to employees would consume the least amount of financial sources. According to System Safety guidelines, the prevailing methods of implementing an accident prevention program include system re-engineering, administrative reform, and work practice controls (Brown, 1976; Gloss & Wardle, 1984). If system re-engineering and administrative reform are too costly to adopt, work practice control (i.e., safety training) is the most cost-effect method to reduce risks and prevent potential accidents. The safety training should be mandatory or routine. Otherwise, the effectiveness of training would be lower-than-expected (Bowen & Lu, 2004b; Lu, 2003; Vincoli, 1993).

The doctrine of System Safety is very useful in accident prevention and safety enhancement. Aviation safety enthusiasts could utilize System Safety tools like the FTA model to identify potential hazards associated with airline operation and to recommend needed countermeasures and trainings for employees. Despite the immediate goal for the aviation industry to regain its revenue after the 9/11, maintaining a risk-free aviation environment should be positioned as the top priority for airlines and our government. Even though the airline industry is extremely safe in the U.S., accidents are still a threat to the flying public because accidents will occur periodically and will claim lives again. From the public's standpoint, each accident is a metaphor for either the government's or the airline's failure to

adequately protect its clients. This study has demonstrated that using System Safety tool is another viable approach to achieve the goal of zero accidents.

FUTURE STUDY

Despite free publications offered by the FAA regarding severe weather, in order to proactively reduce aircraft accidents resulting from turbulence and bird hazard/FOD, the aviation community needs to put more effort into meteorological, technological, and biological studies. In the future application of System Safety techniques, using computer software could dramatically help System Safety managers in different segments of the aviation industry simulate hazards and provide safety trainings scenarios promptly and accurately. With the help of computer technologies tailored for risk analysis, the application of FTA or other System Safety tools can be applied to a greater extent.

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APPENDIX A

RISK MATRIX, SEVERITY & PROBABILITY

Risk Matrix*

Frequency	Catastrophic (I)	Critical (II)	Marginal (III)	Negligible (IV)
Frequent (A)	1A	2A	3A	4A
Probable (B)	1B	2B	3B	4B
Occasional (C)	1C	2C	3C	4C
Remote (D)	1D	2D	3D	4D
Impossible (E)	1E	2E	3E	4E

* A "Risk" falling into this category [1A, 2A, 3A, 4A, 1B, 2B, 1C] is "Unacceptable"

A "Risk" falling into this category [1D, 2C, 3B, 3C, 4B] is "Undesirable"

A "Risk" falling into this category [1E, 2D, 2E, 3D, 4C] is "Acceptable With Review"

A "Risk" falling into this category [3E, 4D, 4E] is "Acceptable Without Review"

The determination of "Unacceptable," "Undesirable," "Acceptable With Review," or "Acceptable without Review" is based on a System Safety analyst's subjective decision-making based on the onsite situation from case to case.

Risk Severity (S) and Probability (P) are defined as:

Risk Severity (S)

Description	Category	Mishap Definition
Catastrophic	I	Death or system loss/failure
Critical	II	Severity injury, occupational illness, or system damage
Marginal	III	Minor injury, occupational illness, or system damage
Negligible	IV	Other

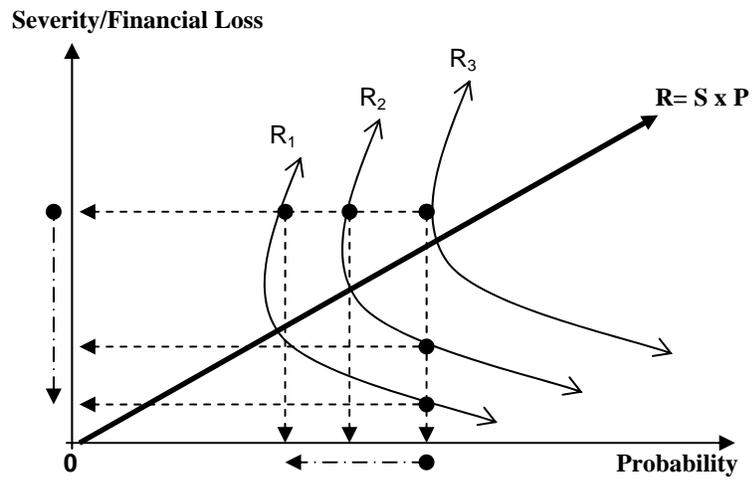
Risk Probability (P)

Description	Level	Mishap Definition
Frequent	A	Likely to occur frequently
Probable	B	Will occur several times during the life of an item
Occasional	C	Likely to occur sometimes in the life of an item
Remote	D	Unlikely, but may possibly occur in life of an item
Impossible	E	So unlikely, assumed that hazard will not occur at all

Source: DOD MIL-STD-882B System Safety Program Requirements (1984)

APPENDIX B

RISK CHART



Note. The product of Risk Probability (P) and Risk Severity (S) is equal to Potential Risk (R) thus in System Safety concept $R = P \times S$. The forming of a "Risk Chart" above was converted from the original *Risk Matrix* and generates a bivariate curve for a better understand and interpretation.

APPENDIX C

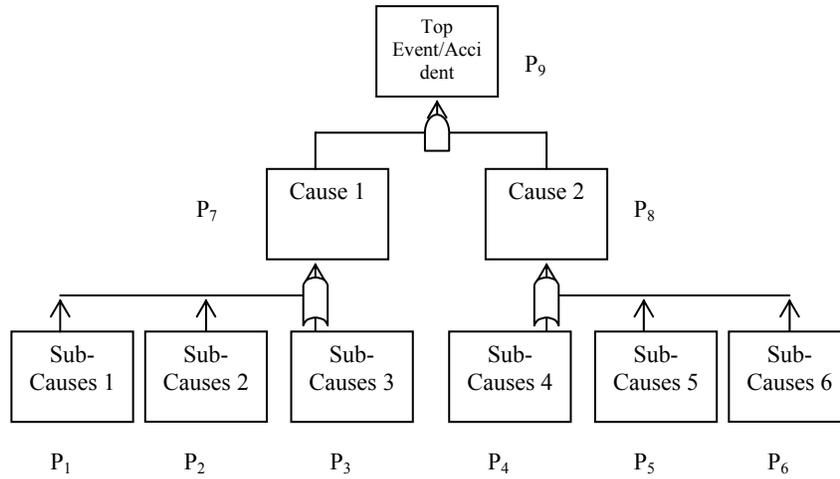
SYSTEM SAFETY WORKSHOPS AND CONFERENCES –
CONTENT ANALYSIS

	2001	2002	2003	2004
System Safety Management	X	x	x	X
Aviation System Safety Program (AvSP)	X	x	x	X
FAA-Airlines Collaboration	X	x	x	X
Data Collection & Risk Analysis	X	x	x	X
System Risk Management (SRM) & Safety Culture		x	x	X
Flight crews-centered	X	x		X
Non-flight crews-centered	X	x	x	X
All aviation workers	X			
Air Carrier Operations System Model (ACOSM)	X			
Aviation Safety Action Program (ASAP)	X	x		X
Flight Operational Quality Assurance (FOQA)	X	x		X
Advanced Quality Program (AQP)	X			
Aviation Safety Reporting System (ASRS)	X			X
Continuous Analysis and Surveillance System (CA	X			
Maintenance Resource Management (MRM) traini	X	x		
Human Factor CRM training	X	x	x	X
Case-based training/Naturalistic Decision-making	X	x	x	X
Regulations	X	x	x	
Cost-benefit and Safety Investment	X	x	x	X
Failure Mode and Effective Analysis (FMEA)		x		
Concept				
Failure Mode and Effective Analysis (FMEA)				
Application				
Fault Tree Analysis (FTA) Concept		x		
Fault Tree Analysis (FTA) Application				
Risk Control Management (RCA)				x
Hybrid Causal Modeling			x	x

Note. The origin of this Content Analysis Table was statistically extracted from the research projects and papers presented at the FAA System Safety workshops and conferences between 2000 and 2004. As shown in the above table, most researches either focused on the advocate of using System Safety concepts or risk analysis covering trend study. Researchers did not apply tools (i.e. FTA or FMEA) to their studies for a demonstration. Especially, there were only two papers explained FMEA and FTA techniques over the past four years. Yet no further application was found.

APPENDIX D

BASIC LOGICS OF FAULT TREE ANALYSIS



Note. The Sub-Causes must be preconditions of the upper level accident Cause; and Causes are preconditions of the Top-Event/Accident. P_i ($i = 1\sim 9$) represents the risk probability associated with each specific “cause” or “factor.”

Note:  represents “AND” gate, while  represents “OR” gate. Other logical gates could be used into *tree* analysis based on different cases, purposes or situations.

APPENDIX E

TERMINOLOGY OF ACCIDENT CAUSES

In this study, the causes leading to an accident were categorized and defined as the following for a better understanding of research findings:

Flight operation: an accident was caused by cockpit crews

Turbulence: an accident was caused by turbulence (in-flight, clear air, wake turbulence)

Maintenance: an accident was caused by aircraft maintenance personnel

Ground crew: an accident was caused by ground crews (truck driver, beltloader or tug operator, ramp agents, etc.)

Foreign Object Damage (FOD): an accident was caused by birds, animals, and any objects that do not belong to aircraft itself

Flight Attendant: an accident was caused by flight attendant's inadequate emergency actions

Air Traffic Control (ATC): an accident was caused by air traffic controller's misjudgment

Manufacturer: an accident was due to manufacturer's design, official inspection manuals, etc.

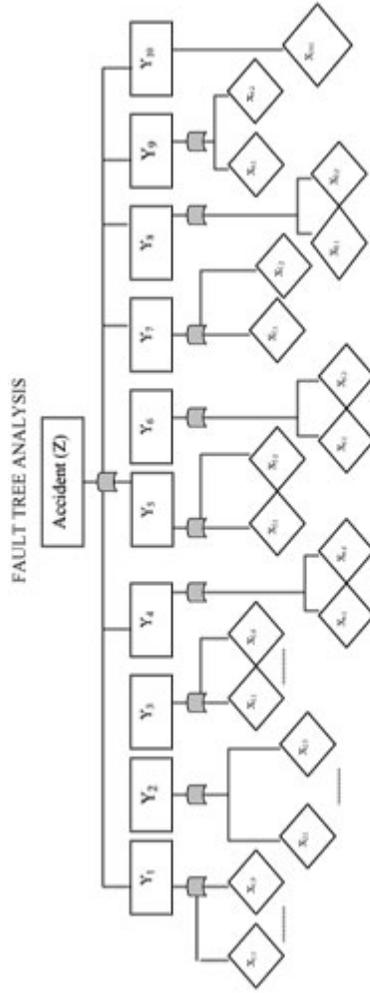
Passenger: an accident was caused by passengers themselves

FAA: an accident was caused by FAA's discretionary function regarding certificate approval, inspection, etc.

Non-flight Error: a combination of maintenance and ground crew's operational mistakes.

APPENDIX F

FAULT TREE ANALYSIS



Z: Top level event (Accident); Y: Cause of accident; X: root factor of the cause of accident

Domino effect ($X \rightarrow Y \rightarrow Z$) exists and was based on the "OR" gate logic, , in System Safety.

Y1: Flight operation - X1,1: situation awareness; X1,2: misjudgment; X1,3: weather; X1,4: communication; X1,5: operational deficiency; X1,6: SOPs; X1,7: over-reaction; X1,8: physical fatigue; and X1,9: weather ignorance
 Y2: Turbulence - X2,1: weather awareness; X2,2: inadequate training; and X2,3: passengers' non-compliance
 Y3: Maintenance - X3,1: QAC; X3,2: SMPs; X3,3: FAA's incorrect data; X3,4: training; X3,5: rushing service; and X3,6: ignorance
 Y4: Ground crew - X4,1: awareness; X4,2: communication; X4,3: QAC; X4,4: ignorance; X4,5: fatigue; and X4,6: health and medication
 Y5: FODs - X5,1: birds; and X5,2: deer
 Y6: Flight Attendant - X6,1: evacuation and emergency procedures; X6,2: communication; and X6,3: cabin training
 Y7: ATC - X7,1: ATC service; and X7,2: flight separation
 Y8: Manufacturer - X8,1: manual; and X8,2: design

APPENDIX G

SIMULATING THE PROBABILITY OF THE TOP-LEVEL EVENT

