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Analyzing aviation safety: Problems, challenges, opportunities

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ABSTRACT

This paper reviews the economic literature relating to aviation safety; analyzes the safety record of commercial passenger aviation in the United States and abroad; examines aviation security as a growing dimension of aviation safety; and identifies emerging issues in airline safety and challenges for aviation safety research. Commercial airline safety has improved dramatically since the industry's birth over a century ago. Fatal accident rates for large scheduled jet airlines have fallen to the level where (along many dimensions) aviation is now the safest mode of commercial transportation. However, safety performance has not been evenly distributed across all segments of commercial aviation, nor among all countries and regions of the world. The finding that developing countries have much poorer safety records has been a persistent conclusion in aviation safety research and continues to be the case. Unfortunately, operations data are not available for many of the airlines that experience fatal accidents, so it is not possible to calculate reliable fatality rates for many segments of the worldwide aviation industry. Without more complete information, it will likely be difficult to make substantial improvements in the safety of these operations. Challenges to improving aviation security include: how much to focus on identifying the terrorists as opposed to identifying the tools they might use; determining how to respond to terrorist threats; and determining the public versus private roles in providing aviation security. The next generation of safety challenges now require development and understanding of new forms of data to improve safety in other segments of commercial aviation, and moving from a reactive, incident-based approach toward a more proactive, predictive and systems-based approach.

This paper reviews aviation safety performance and challenges. It begins with a brief introduction in Section 1, followed by a review of the economic literature relating to aviation safety in Section 2. Section 3 analyzes the safety record of commercial passenger aviation in the United States and abroad. Section 4 discusses aviation security as a growing dimension of aviation safety. Section 5 identifies emerging issues in airline safety, along with the challenges for aviation safety research. Section 6 provides a summary and major conclusions.

1. Introduction

Scheduled passenger airline service has become very safe.[1] With one passenger fatality per 7.1 million air travelers, 2011 was the safest year on record for commercial aviation worldwide[2] (Michaels & Pasztor, 2011). The International Air Transport Association reported that the global airline accident rate was one accident for every 1.6 million flights, a 42 percent improvement since 2000 (Hersman, 2011). The improvement in safety during flight has led to increased attention to on-ground risks in the industry – hazards that occur before take-off and after landing – as the quest for improving commercial aviation continues (Pasztor, 2011).

Improvement in safety has come from many sources over the years. Technological improvements in aircraft, avionics, and

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[1] There are a number of sources for airline safety data and analysis. From the governmental side, these include the FAA (See http://www.faa.gov/data_research/safety/ and http://www.asias.faa.gov/portal/page/portal/ASIAS_PAGES/ASIAS_HOME); the National Transportation Safety Board (http://www.ntsb.gov/); and the International Civil Aviation Organization (http://www.icao.int/Safety/Pages/default.aspx). Nongovernmental sources include the Flight Safety Foundation (www.flightsafety.org and http://aviation-safety.net/index.php), Airline Safety (http://www.airlinesafety.com/), AirSafe.com (http://www.airsafe.com/), and Ascend FlightGlobal (http://www.ascendworldwide.com/what-we-do/ascend-data/accident-and-loss-data/).

[2] In 2004, there was one fatality per 6.4 million passengers on commercial flights worldwide.

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engines have contributed to the betterment of the aviation safety record. Accident investigations have been aided by improved cockpit voice recorders and flight data recorders. The development and use of ground proximity warning devices on aircraft have all but eliminated a certain type of accident known as controlled flight into terrain for aircraft equipped with such devices. Aircraft engines are more reliable and fail less often. Indeed, improvements in aircraft components have resulted in fewer accidents that involve equipment failure. Pilot training has improved through the use and evolution of sophisticated flight simulators in both initial and recurrent pilot training. Pilot training has also benefitted immensely from improved understanding of human factors and the application of that understanding to training and regulations. Navigational aids and air traffic management have also improved, making flight safer. Improved weather forecasting and better understanding of weather phenomena such as downdrafts and wind shear have also helped.

Another major contributor to the improved safety record can be traced to the careful investigation of past accidents to determine what led to the accidents and what needs to be done to prevent such events from occurring again. This reactive approach to improving aviation safety has been enhanced by the thorough analyses of data from numerous accidents, which has aided in the identification of recurring patterns or risk factors that are not always apparent when individual accidents are investigated. More recently, proactive approaches to determining ways to improve safety have become increasingly popular. An example of such a proactive approach is the analysis of incident data to identify areas of increased risk that may lead to an accident.

2. Economic analysis of aviation safety

As might be expected, much of the literature on aviation safety has its roots in engineering and technology (Rodrigues & Cusick, 2012; Stolzer, Halford, & Goglia, 2008). Much of the economic analyses of airline safety in the 1980s and early 1990s focused on the potential safety effects of deregulation and liberalization, and the comparative safety performance of industry segments, especially new entrant carriers. Although the conclusions were mixed, Savage shows that safety records for new entrant airlines in the early 1990s were worse than for established carriers (Savage, 1999). In the past decade though, there has been little variation in safety among the major airlines in the developed world. Efforts to analyze comparative safety performance in the developing world have been hampered by problems of data availability and inconsistency.

2.1. Reactive versus proactive approaches to the analysis of aviation safety

Traditionally the focus of research on aviation safety has been on analyzing accidents, investigating their causes, and recommending corrective action. More recently, in addition to this reactive approach to improving aviation safety, increased emphasis has been placed on taking a proactive approach. This approach involves identifying emerging risk factors, characterizing these risks through modeling exposure and consequences, prioritizing this risk, and making recommendations with regard to necessary improvements and what factors contributed to the accident. This approach places more emphasis on organizational and systematic risk factors (GAO, 2012).

2.2. Economic (reactive) analyses of safety

While the worldwide aviation safety record has improved dramatically over time, these safety advances have not been evenly distributed across all segments of commercial aviation nor among all countries and regions of the world (Barnett, 2010; Barnett & Higgins, 1989; Barnett & Wang, 2000; Oster, Strong, & Zorn, 1992, 2010). A handful of researchers, in addition to those identified above, have tried to identify what causes these variations in accident rates among air carriers.

The effect of profitability on an airline's safety record is one area that has received a fair amount of attention, with mixed results. Research performed in 1986 by Golbe found no significant relationship between airline profitability and safety. Rose (1990) found a significant relationship between profitability and lower accident rates. Upon a closer analysis of the data, it was determined that this correlation between profitability and safety was present for medium and small airlines but was not statistically significant for larger airlines. A 1997 analysis of the Canadian airline industry by Dionne, Gagné, Gagnon, and Vanasse (1997) identified a negative relationship between profitability and safety for the smallest airlines analyzed. While on the surface this result might seem counterintuitive, the investigators discovered that those small airlines that spent more on maintenance, which would negatively impact the bottom line, experienced lower rates of accidents. A recent update to the Rose analysis found a negative relationship between financial performance and accident rates among air carriers, especially among smaller regional carriers (Raghavan & Rhoades, 2005). Specifically it was found that the negative relationship between profitability and safety existed for both major and regional airlines but was statistically significant only for the latter.

Noronha and Singal (2004) use a slightly different methodology to address the question whether an airlines' financial health has an impact on its safety record. They note that previous studies have identified a weak or non-existent relationship between financial health and safety and posit that this may be due in part to airlines enhancing their profitability in the short run by reducing investment in safety. Instead of using profitability as a measure of financial health, they use bond ratings as a proxy for financial performance. It is determined that airlines with stronger bond ratings are safer than those airlines that are financially weak. The authors emphasize that although they found a correlation between financial health and airline safety, they were unable to establish causation.

Savage (2012) employs a different approach to determining if there is a link between an airline's finances and its safety record. In theory, an airline would think about safety as a quality indicator that would reduce the competitive focus on prices. In other words, by establishing a better safety record than its competitors, an airline should be able to increase its profitability. Despite economic theory suggesting that airlines should attempt to differentiate themselves from their competitors in order to augment their bottom line, it appears they do not do this in practice, especially for airlines serving a particular market segment or geographic region. He attributes this phenomenon to the difficulty airlines have effectively communicating safety differentials and the failure of consumers to adequately internalize what information they do receive. This in turn means consumers are unwilling to pay a premium for safety enhancements they fail to perceive.

In a re-examination of the link between an airline's profitability and its safety record, Madsen (2011, p. 3) suggests that the "strikingly inconsistent results" in the existing empirical literature are due to an inflection point in the relationship between profitability and safety. His analysis "…demonstrates that safety fluctuates with profitability relative to aspirations, such that accidents and incidents are most likely to be experienced by organizations performing near their profitability targets" (Madsen, 2011, p. 23). In other words, if an airline is slightly below its profitability target, it has an incentive to increase its risk of accidents by spending less on safety. Or, if it is slightly above its target, a reduction in spending on safety can have a significant effect on its ability to remain above the profitability target. Conversely, when an airline is substantially above or below its profitability target, the incentive to reduce spending on safety is considerably less. In the former situation, reductions in spending on safety (increased accident risk) will not have much effect on the airline's bottom line. In the latter situation, an airline has a desire to improve its financial status and one way to achieve this goal is by reducing its risk of accidents (spend more on safety). However, Madsen's research does not address the mechanisms by through which safety may be compromised, nor does he attempt to classify accidents or incidents that may be more associated with such organizational behavior. For example, if airlines reduced safety investments to meet safety goals, then we might expect to see reductions in maintenance cycles or in pilot training. In practice, many of these aspects of aviation safety are largely built into operational cycles and are also governed by labor and regulatory agreements.

Others have investigated the link between maintenance and aviation safety. Marais and Robichaud (2012) look at the effect that maintenance has on aviation passenger risk. They found a small but significant impact of improper or inadequate maintenance on accident risk. In addition, they determined that accidents that have maintenance as a contributing factor are more serious than accidents in general. Another study has implications for the effect that aging aircraft may have on accidents and overall safety levels. In an investigation of the effect the adoption of strict product liability standards has had on the general aviation industry, it was found that liability insurance costs for new planes increased significantly (Nelson & Drews, 2008). As a result, manufacturers raised prices appreciably which had a considerable negative impact on the sale of new aircraft. Consequently the average age of the general aviation fleet increased. The authors projected that the general aviation accident rate and the number of fatalities would have been substantially lower if new sales had not been adversely affected. They attribute this decrease in safety to the presence of older, more accident prone aircraft.

2.3. Proactive approaches to safety analysis

As the safety record of the aviation industry improves it has become increasingly evident that the probability of an accident, especially a fatal accident, is extremely low. This makes it ever more apparent that reliance on analyses of accidents after they have occurred provides only a partial picture of aviation safety. The result has been increased attention being paid to identifying ways to proactively determine how changes in the aviation system affect the risk of accidents. This argument is based on work by Reason on modeling of organizational accidents (Reason, 1990, 1995, 1997, 2000, 2005). Reason favors an integration of reactive and proactive approaches to the analysis of safety – what he refers to as the interactive phase of system operations, where safety, operational, and management systems interact. This conceptual framework has become the basis for "swiss cheese" models of safety management, in which most accidents are seen as the result of multiple failures in a system. In Reason's work, for an accident to occur, all of the holes (failures in safety defenses) in multiple slices of Swiss cheese need to line up for an accident to occur. This perspective is the basis for much of the development and emphasis on Safety Management Systems. For example, the Federal Aviation Administration (FAA) is placing more emphasis on a proactive approach through its use of Safety Management Systems in an attempt to identify and reduce risks (GAO, 2010a).

Taking a proactive approach to enhancing aviation safety is a complex endeavor (Roelen, 2008). To determine and assess risk prospectively involves attempting to identify the complex chain of events that generally are associated with an aviation accident. Over the years a number of approaches have been taken. These approaches include proactive causal models, that focus on anticipating problems that lead to accidents; collision risk models, which focus on the loss of separation between aircraft both on the ground and in the air; human error models, that attempts to trace the series of reactions that occur to an initial incorrect execution of an initial task; and third party risk models, that analyze the probability that a crashing aircraft kills or injures an individual on the ground (Netjasov & Janic, 2008).

Extending Reason's ideas, Lofquist argues that the use of traditional safety metrics – traditional reactive and proactive analysis – fails to capture how numerous factors in a complex aviation system might be the culprit. "When accidents do occur, we have a measurable indication that things are not safe, but when nothing happens…we do not know if this is due to properly functioning safety processes, or due to good fortune" (Lofquist, 2010, p. 1523). Aviation has always relied on overlapping and interacting systems to manage safety and create the margin of safety. By focusing on the root cause of an accident, organizational and managerial conditions that contributed to the accident may be overlooked.

Clearly a more comprehensive approach to the analysis of aviation safety, along the lines of what Reason and Lofquist suggest, can be very useful in developing safety practices and oversight. However, more traditional reactive analytical approaches remain useful in helping to identify segments of the aviation industry where safety performance is problematic relative to the rest of the industry. In this vein, there are important research opportunities in the development of firm level behavioral data concerning safety investments, more disaggregation of incident data, and improving data availability and quality about safety performance in specific regions and segments of aviation.

3. The worldwide airline safety record 1990–2011

3.1. Determining the causes of the accident

Differences in accident rates can help identify less safe segments of aviation, but such differences provide little insight into why safety may vary among segments of the industry or between regions of the world and little guidance into how to improve safety in these less safe segments. To understand why safety may vary across segments or regions and to develop targeted programs to improve safety, the causes of a large number of accidents must be examined.

All portions of a flight do not pose the same risk of an accident. Table 1 shows the percent of flight time that occurs in each phase of a typical flight and also the percent of fatal accidents that occur

Table 1
Fatal accidents and exposure by phase of flight, 2002–2011.

Phase of flight	Percent of	
	Exposure	Fatal accidents
Taxi, load, unload, parked, tow	0	11
Takeoff	1	10
Initial climb	1	5
Climb (flaps up)	14	5
Cruise	57	11
Descent	11	4
Initial approach	12	14
Final approach	3	16
Landing	1	20

Exposure is the percentage of flight time estimated for a 1.5 h flight. Source: Boeing, *Statistical Summary*, 2012, p. 20.

during that phase. Before the flight takes off and after it lands, taxi, loading/unloading, and other ground operations result in 11 percent of fatal accidents, but the fatalities in these accidents typically involve ground personnel rather than on board fatalities. The takeoff and initial climb phases of flight each account for about 1 percent of flight time but account for 10 percent and 5 percent respectively of fatal accidents. Climb (once the flaps are up) is a less risky phase and accounts for 14 percent of flight time but only 5 percent of fatal accidents. Cruise, the least risky phase, accounts for the majority of flight time, 57 percent, but only 11 percent of fatal accidents. The descent, approach, and landing phases become progressively more risky. Descent accounts for 11 percent of flight time and 4 percent of fatal accidents while initial approach accounts for 12 percent of flights and 14 percent of fatal accidents. Finally, final approach and landing account for 3 percent and 1 percent of flight time but account for 16 percent and 20 percent of fatal accidents respectively.

Understanding when accidents are most likely to occur is helpful in targeting approaches to improve safety, but to reduce accidents it is also necessary to try to determine why they occur. An enormous amount of effort goes into investigating major airline accidents, both in the United States and abroad. The information gained from those investigations has been a critical part of improving aviation safety by reducing the chances that the factor or factors that led to one accident will cause similar accidents in the future. While safety has been improved by considering each accident as an individual event, learning from that event, and working to prevent similar accidents from occurring in the future, there is also much to be gained by looking broadly at the causes of accidents and comparing them over time, across different segments of aviation, and across countries and regions.

Analyzing the causes of accidents involves difficult choices. Aviation accidents are rarely the result of a single cause. Rather, accidents are usually the culmination of a sequence of events, mistakes, and failures. Often, had any of the individual events in the sequence been different, the accident would not have happened. Take a very simple example of an engine failure during takeoff where the crew then fails to take the needed actions to land the plane safely with the result of an accident. Had the engine not failed, there would not have been an accident. Had the crew responded to the engine failure quickly and properly, there would not have been an accident. How might you analyze causes in an accident like this?

How one analyzes causes depends on the goal of the analysis. If the goal is to learn as much as possible from an individual accident and take steps to reduce the chances of an accident like that happening again, then the analysis of the example above should consider both the engine failure and the improper crew response as causes. Efforts could then be directed at determining why the engine failed and taking steps to reduce future engine failures. Other efforts could be directed at determining why the crew did not respond properly and taking steps to improve future crew responses. Much of the past improvement in aviation safety has come from lessons learned from detailed analyses of individual accidents. In its accident investigation reports, the National Transportation Safety Board (NTSB), will typically list both multiple causes of an accident as well as additional factors that contributed to the accident.

An example of the approach of assigning multiple causes to an accident is the Human Factors Analysis and Classification System (HFACS) developed originally for the Department of Defense and more recently applied to civilian aviation accidents (Shappell & Wiegmann, 2000). HFACS has focused on aircrew behavior but could also be applied to human factors in maintenance, air traffic management, cabin crew, and ground crew. The basic approach uses Reason's (1990) concept of latent and active failure and considers four levels of failure: 1) unsafe acts, 2) preconditions for unsafe acts, 3) unsafe supervision, and 4) organizational influences. Each of these levels is further divided into multiple causal categories with many individual error categories within each causal category (Wiegmann et al., 2005). One challenge with upwards of 150 separate human factors error categories is that each accident can appear unique. To look for trends over time or patterns across accidents, these error categories are often aggregated back into the causal categories. In one study of human error in commercial aviation accidents, the results were reported aggregated into 18 causal categories (Shappell et al., 2004). Not all accidents were included in the analysis, only those where there was some error by the aircrew. The results were reported as the number of accidents in the data set that were associated with one or more of the error categories that make up each causal category.

If the goal of the analysis is to examine how the causes of accidents might have changed over time or to compare the causes of accidents in different segments of aviation or across different countries or regions, then another approach would be to classify each accident according to a single cause. Admittedly assigning a single cause to an aviation accident is a simplification. One advantage of this simplification is that it is possible to compare a much broader range of accidents. Not all accident investigations are equally detailed, in part because not all aircraft are equipped with cockpit voice recorders or flight data recorders. Also, not all accidents are investigated by organizations with the resources or technical expertise of the National Transportation Safety Board in the United States, the Air Accidents Investigations Branch in the United Kingdom, the Bureau of Enquiry and Analysis for Civil Aviation Safety in France, or several other organizations in the developed world. With many commercial aviation accidents and with many general aviation accidents, there simply is not as much information about the causes of the accidents available as for an accident by a major international airline investigated by one of the top accident investigation organizations. If more information is available for accidents in some sectors of aviation than others or in some countries than others, then there may be a tendency to find more errors in accidents where more information is available which could result in giving those accidents more weight in aggregate statistics. By assigning a single (primary) cause to each accident, each accident is weighted equally and this potential bias is avoided.

There are two basic approaches to assigning a cause or causes to an accident. One approach would be to assign the cause that was the last point at which the accident could be prevented. Pilot error would be indicated as the cause of the accident provided in the example above. This approach offers clear interpretation of the results, but the results are unlikely to be very informative because pilot error will be assigned as the cause very frequently. During in-flight emergencies pilots are often the final link in the chain of events that led up to the accident. Many times the pilots can be faulted because, at least compared to ideal performance, they should have been able to deal with the emergency successfully. However, the authors believe this places an unreasonable expectation on pilots to be infallible in what often are very trying circumstances where split-second decisions need to be made. Perhaps more importantly, the safety policy implication from such an approach would usually be to improve pilot training. While improving pilot training will almost certainly improve aviation safety, another approach would be to find ways to reduce the number of times pilots were faced with in-flight emergencies that allowed so little room for human error.

A second approach, which is taken in this paper and in the authors' prior work, is to select as the cause the factor that initiated the sequence of events that culminated in the accident. In the case of the above example, engine failure would be identified as the cause of the accident.[3] The assumption behind this approach is that, in the absence of the factor that initiated the chain of events resulting in an accident, the accident could have been avoided. A benefit of focusing on the sequence initiating cause means that when pilot error is identified as the cause, it refers to what may be characterized as an "unforced" pilot error rather than a failure to respond properly to an emergency when there may be a confluence of events that are difficult to respond to regardless of how talented the flight crew is or how good their training was.

Once the basic approach of focusing on the sequence-initiating cause has been selected, the next challenge is how to assign causes to a large number of accidents. The authors have developed, and refined over many years and after reviewing thousands of accidents, a set of rules and definitions to guide how causes are assigned to accidents. The goal in developing these rules is to be consistent in assigning causes so that it is possible to make meaningful comparisons of how the distribution of causes varies over time, across different segments of the industry, and across countries of regions. It is also important to recognize that for some accidents there simply isn't enough information available to assign a cause. Appendix A provides a description of the causation categories.[4]

The authors are not arguing that focusing on a single "sequence initiating cause" is superior to other approaches. Each approach has strengths and limitations and each can provide unique and important insights. The critical part of any analysis is to understand what insights can and cannot be gained from the specific kind of analysis. Instead, the authors are arguing that a careful application of this approach has the potential to provide useful insights into some aspects of aviation safety.

3.2. *Aviation safety in US commercial passenger operations*

The focus of this paper is on the safety of commercial passenger operations in fixed-wing aircraft, both in the United States and abroad. The analysis is limited to accidents where there was at least one passenger fatality, so that accidents where only crew members were killed or where there were no fatalities were not included. In the United States such operations are provided either under what are known as Part 121 regulations or under Part 135 regulations.[5] Airline passenger service in aircraft with more than 30 seats has always been provided under Part 121 regulations. Traditionally, scheduled commuter service with aircraft with fewer than 30 seats and on-demand air taxi service has been provided under Part 135 regulations, although as discussed below there were changes in 1997 to the regulations under which much scheduled commuter service was provided.

Table 2 shows fatal accidents, passenger fatalities, and the fatality rate measured in passenger fatalities per one million revenue passenger enplanements for Part 121 scheduled service during the 1990 through 2011 period.[6] During this period, there was only one fatal passenger accident in Part 121 nonscheduled services, which resulted in a single passenger fatality so it is not meaningful to calculate a passenger fatality rate for this type of service. In terms of passengers carried, domestic service is over 8 times larger than international service, so it is not surprising that most of the accidents were in domestic service. Since international service is typically provided in larger aircraft, it is again not surprising that even with fewer accidents; the numbers of fatalities are about the same in domestic and international service. The fatality rate, as measured by passenger fatalities per one million enplanements was 0.06 for domestic service and 0.49 for international service for a combined rate of 0.11. Over this period, the international fatality rate was noticeably higher than the domestic rate.

Table 2
Part 121 scheduled passenger service, 1990–2011.

	Total (system)	Domestic service	International service
Fatal accidents	26	19	7
Passenger fatalities	1494	772	722
Passenger fatalities per million enplanements	0.11	0.06	0.49

Source: Accident and passenger fatality data from NTSB accident reports accessed through ASIAS (FAA, 2012a). Revenue Passenger Enplanement data from U.S. Department of Transportation (2012).

Table 3
Causes of part 121 accidents, 1990–2011.

Accident cause	Share of accidents	Share of fatalities
Equipment failure	31%	49%
Seatbelt/turbulence	8%	0%
Weather	8%	7%
Pilot error	27%	20%
Air traffic control	4%	1%
Ground/cabin crew	8%	7%
Other aircraft	0%	0%
Terrorism/conflict/criminal	15%	16%
Total	100%	100%
Unknown cause/other	0%	0%

Source: Authors' calculations based on NTSB accident reports accessed through ASIAS (FAA, 2012a).

Table 3 shows the distribution of causes for these accidents. Nearly one third of the accidents (accounting for nearly half the fatalities) were the result of some form of equipment failure. Pilot error was the next most important cause, accounting for 27 percent of the accidents with 20 percent of the fatalities. Perhaps not surprisingly, the next biggest cause was terrorism, since this time period included the events of September 11, 2001 where 232 passengers were killed. Some analysts whose focus is on helping airlines preventing accidents often exclude terrorism related events from their analysis.[7] Terrorism-related events have been left in for the analyses in this paper, including the rates in Table 2, for three reasons. First, the focus is on the risk to passengers from air travel, whether that risk is due to accidents or deliberate terrorist actions. Second, terrorism-related aviation events are not uniformly distributed throughout either the various segments of aviation or throughout the various countries and regions of the world, as will

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[3] Throughout the remainder of the paper, the word cause is intended to mean sequence-initiating cause as discussed above.

[4] The Appendix A lists 9 cause categories. Within these broad cause categories are 44 separate causes each of which has rules for determining which cause should be assigned to the accident. These detailed causes are not used in this paper, so are not included in the appendix. One of the categories includes accidents where the cause could not be determined or where the aircraft was not recovered and there was no accident investigation thus the cause was unknown. These accidents were excluded from the distributions of causes presented in the tables in the paper. For more detail on the rules for assigning causes, see Oster et al., 1992, Appendix B.

[5] Part 121 and Part 135 refer to the parts of Title 14 of the Code of Federal Regulations that contain the regulations for these portions of civil aviation.

[6] For both accidents involving U.S. airlines and foreign airlines, only accidents that resulted in passenger fatalities are examined, so the term fatal accidents refers to accidents with at least one passenger fatality.

[7] If the September 11, 2001 accidents were not included, the domestic passenger fatality rate would have been 0.04 passenger fatalities per million enplanements.

be shown later in this paper. Finally, from a passenger perspective, the air travel experience reflects efforts to prevent terrorist attacks on aircraft, particularly in the United States, so this paper will also examine terrorism and the response to it.

While the Part 121 air carriers carry the vast majority of commercial passengers in the United States, there is also substantial passenger service offered by air carriers operating under Part 135. Part 135 air carriers operate smaller aircraft in both scheduled (often referred to as commuter) and nonscheduled (often referred to as on-demand) service typically into and out of smaller airports than those served by Part 121 air carriers. Reliable enplanement data are not available for all of the Part 135 industry, so it is not meaningful to calculate passenger fatality rates for the Part 135 industry. Without enplanement data it is also difficult to compare the relative sizes of Part 121 and Part 135 operations. Flight hour data are available however, and Part 135 flight hours, scheduled and nonscheduled combined, were about 27 percent of Part 121 scheduled airline flight hours over the 1990 through 2011 time period. The nonscheduled portion of the Part 135 industry is much larger than the scheduled portion. Indeed, in 2010 nonscheduled Part 135 flight hours were over nine times scheduled Part 135 flight hours. Since Part 135 flights are typically much shorter than Part 121 flights, the comparative figures on aircraft departures would almost certainly be much closer, were such data available.

Comparable figures are available for passenger fatalities. Between 1990 and 2011, 576 passengers were killed in Part 135 accidents. This figure represents 75 percent of the number of passenger fatalities in scheduled Part 121 domestic operations over the same time period. Part 135 passenger fatalities rarely get the same media or public attention as Part 121 fatalities, perhaps because the average number of passengers killed in a Part 121 accident was 57 while for a Part 135 accident it was less than four. Part 135 operations nevertheless are responsible for a significant number of commercial aviation passenger fatalities and improving Part 135 safety should be a focus for aviation safety policy.

Table 4 shows the distribution of causes for Part 135 fatal accidents over the 1990–2011 period. Comparing the first two columns of Table 4 with Table 3, it's evident that the distribution of causes is markedly different. Whereas with Part 121 accidents, pilot error is the sequence initiating cause in 27 percent of the accidents accounting for 20 percent of the passenger fatalities, for Part 135 accidents, pilot error is the cause in 70 percent of the fatal accidents representing 61 percent of the passenger fatalities. Equipment failure, on the other hand, plays a somewhat smaller role in Part 135 accidents than in Part 121 accidents.

The reasons for the greater role of pilot error in Part 135 accidents are not well understood. One hypothesis is that Part 135 pilots have less experience because many pilots' career progressions involved starting in Part 135 operations and then moving on to Part 121 operations they gained more experience. Unfortunately, a first step in testing this hypothesis would involve comparing the experience levels of pilots who crashed with those of pilots in the same industry segments who did not crash. While the experience of pilots who crashed is available as part of most NTSB accident investigations, information on the experience levels of the pilots who did not crash, including how much they fly and in what type of service for which carriers, is not readily available.

Within the Part 135 industry, the distribution of accident causes for scheduled and nonscheduled service are very similar, so they are not presented. However, the distributions of causes for Part 135 accidents in Alaska service is noticeably different than for service outside of Alaska, as the right most four columns of Table 4 show. For Part 135 service in Alaska, pilot error is even more prominent, accounting for 83 percent of both accidents and fatalities. The reasons for these differences are also not understood. Aviation plays a much more prominent role in transportation in Alaska than in the rest of the United States because of the many remote communities not connected by highway networks. Alaska is a very challenging aviation environment in part because of weather, rugged terrain, more float plane operations, more operations into and out of unpaved runways, and fewer navigational and landing aids. Such an environment conceivably provides more opportunities for deficiencies in pilot flying skills to become apparent.

In December 1995, the FAA implemented the Commuter Safety Initiative intended to set a single level of safety for most travelers in scheduled airline service by requiring operators of aircraft with between 10 and 30 seats who had been permitted to operate under Part 135 regulations to operate instead under Part 121 regulations (U.S. Department of Transportation, 2000). These regulations contained more demanding provisions for flight crew training and qualifications as well as flight duty times and crew rest requirements. The regulations took effect on March 20, 1997. Table 5 shows the average number of fatal accidents and passenger fatalities per year for Part 135 carriers in the 8-year period before the Commuter Safety Initiative took effect, for the remaining Part 135 carriers in the 8-year period after it took effect, and in the 6-year period through 2011. The initiative was directed at scheduled service and, as the right hand side of the table shows, the average number of accidents and passenger fatalities dropped dramatically as carriers moved out of the Part 135 industry into the Part 121 industry and continued to drop in the most recent period. However, as the center of the table shows, there were also large reductions in accidents and passenger fatalities in the nonscheduled portion of the industry after 1997, so the safety performance of the scheduled portion of the industry would likely have improved some even without the initiative. As these former

Table 4
Causes of part 135 accidents, 1990–2011.

Accident cause	Total		Non-Alaska		Alaska	
	Accidents	Fatalities	Accidents	Fatalities	Accidents	Fatalities
Equipment failure	23%	27%	27%	31%	15%	15%
Seatbelt/turbulence	0%	0%	0%	0%	0%	0%
Weather	4%	6%	5%	8%	2%	2%
Pilot error	70%	61%	64%	54%	83%	83%
Air traffic control	1%	2%	1%	3%	0%	0%
Ground/cabin crew	0%	0%	0%	0%	0%	0%
Other aircraft	1%	3%	2%	4%	0%	0%
Terrorism/conflict/criminal	1%	0%	1%	0%	0%	0%
All causes	100%	100%	100%	100%	100%	100%
Unknown cause/other	12%	11%	12%	10%	13%	13%

Source: Authors' calculations based on NTSB accident reports accessed through ASIAS (FAA, 2012a).

Table 5
Changes in the part 135 accident record following 1997.

Time period	All service		Nonscheduled service		Scheduled service	
	Fatal accidents	Passenger fatalities	Fatal accidents	Passenger fatalities	Fatal accidents	Passenger fatalities
1990–1997	11.5	44.4	8.0	22.5	3.5	21.9
1998–2005	5.1	19.6	4.4	16.6	0.8	3.0
2006–2011	4.7	10.7	4.5	10.5	0.2	0.2

Source: Authors' calculations based on NTSB accident reports accessed through ASIAS (FAA, 2012a).

Part 135 scheduled carriers moved into the Part 121 portion of the industry, there was not a detectable increase in the accident rates in that portion of the industry, so there is no evidence that Part 121 safety was degraded by the transition of these former Part 135 carriers.

3.3. Commercial passenger operations outside the United States

Safety performance has not been evenly distributed across all segments of commercial aviation nor among all countries and regions of the world (Barnett, 2010; Barnett & Higgins, 1989; Barnett & Wang, 2000; Oster et al., 1992, 2010). Barnett (2010) finds a significant variation in safety rates among countries through a disaggregation of worldwide aviation travel risk. Despite an average passenger death risk per scheduled flight over the 2000–2007 time period of 1 in 3 million, he finds that the death risk per flight is 1 in 14 million for what he categorizes as First-World nations, is 1 in 2 million for Advancing Nations, and 1 in 800,000 for Least-Developed nations.[8]

The finding that developing countries have much poorer safety records has been a persistent conclusion in aviation safety research. For example, Oster et al. (1992) found that accident rates from 1977 to 1990 in Latin America were about seven times higher than those of North America and Western Europe; accident rates in Africa were found to be 15–20 times higher.

The regulatory structure that governs commercial air service varies across different countries, so when looking at commercial passenger operations outside the United States, there is no equivalent of the U.S. distinction between Part 121 and Part 135. Instead, commercial air operations are broken down by domestic versus international and scheduled versus nonscheduled.

Fig. 1 shows the number of fatal accidents by type of service over time. While there is year-to-year variation, the number of accidents showed a clear downward trend from 1995 through 2003, but increased year-to-year variation since then. Without comprehensive operations data for all four segments, particularly domestic nonscheduled service, it's not possible to say conclusively that safety was improving during this period, although other sources have shown that the fatal accident rate for commercial jet aircraft has declined during this period as operations have increased (Boeing, *Statistical Summary*, 2012).

Table 6 shows the fatality rate, measured by passenger fatalities per one million enplanements for each of the four types of service in the first column and the total number of passenger fatalities in the second column.[9] At first glance, the fatality rates shown in the second row of the table appear to be quite similar across the four segments of commercial passenger aviation. However, these fatality rates need to be viewed with caution, as many of the airlines that had fatal crashes during the 1990 to 2011 period did not report operations data to International Civil Aviation Organization (ICAO).[10] The bottom row of the table shows the share of the passenger fatalities from airlines which reported operations data to ICAO during the year in which the fatal accident occurred. In many cases, the airline didn't report any enplanement data to ICAO at all during the period. In other cases, the airline might have reported enplanement data for one or more years, but not for the year in which the fatal crash occurred. In a few cases, the country in which the airline is based is not a member state in ICAO, so the airline did not report data.

As can be seen in the table, domestic scheduled service has a fatality rate of 0.33 passenger fatalities per one million enplanements. This rate is about five times higher than the US domestic rate for large carriers (Part 121). However, only 41 percent of the fatalities were on airlines that reported enplanements to ICAO and are thus included in this rate. With nearly 60 percent of the fatalities not included in the rate, it is difficult to know what the rate would be if all carriers reported enplanement data. Since most of the world's largest and best established airlines report data to ICAO, one can speculate that perhaps many of the airlines who don't report operate less safely. Were that true, then the complete rate that included all the airlines would be even higher, but there is no way to know for sure. International scheduled service has a rate of 0.32 fatalities per million enplanements, which is lower than the U.S. international Part 121 rate, but again is based on only part of the fatal accidents. In the case of international scheduled service, the fatality rate includes 57 percent of fatalities, which is better than for domestic service, but still far from complete. In calculating the U.S. rates, all the Part 121 scheduled airlines report operations data, so the rates include 100 percent of the fatalities. For both domestic nonscheduled service and international nonscheduled service, the fatality rates appear on the same order of magnitude as for scheduled service, but the rates include only a very small portion of the fatalities – 3 percent for domestic nonscheduled service and 17 percent for international nonscheduled service. Again, it would not be surprising if the nonscheduled carriers who

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[8] In his analysis, Barnett defines the First World nations to be Australia, Austria, Belgium, Canada, Denmark, France, Germany, Greece, Iceland, Ireland, Israel, Italy, Japan, Luxembourg, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, United Kingdom, and United States; the Advancing Nations to be Bahrain, Bosnia/Herzegovina, Brazil, Brunei, China, Cyprus, Czech Republic, Hong Kong, India, Jordan, Malaysia, Mexico, Philippines, Singapore, Slovenia, South Africa, South Korea, Taiwan, Thailand, Turkey, and United Arab Emirates; and the Least Developed to be All other nations, excepting some small jurisdictions (e.g., Andorra, Monte Carlo, Aruba) that have little if any aviation on their own.

[9] Operations data used to calculate rates were collected by the International Civil Aviation Organization (ICAO). The ICAO data operations database contains information for 1136 airlines for 182 countries over the 1990–2011 period.

[10] The ICAO data operations database (available through FlightGlobal.com) is the most comprehensive source of international information for commercial aviation. However, the database is incomplete in that not all carriers report data for all years. This is a bigger data issue in recent years, given the growth and dynamism in commercial airlines through liberalization and privatization in emerging markets. For example, China reported no operations data in 1990–1992, and only data for CAAC was reported in 1993 and 1994. By 2000, eight Chinese airlines are represented in the ICAO data, and by 2011 fully 31 Chinese airlines were provided operating data to ICAO.

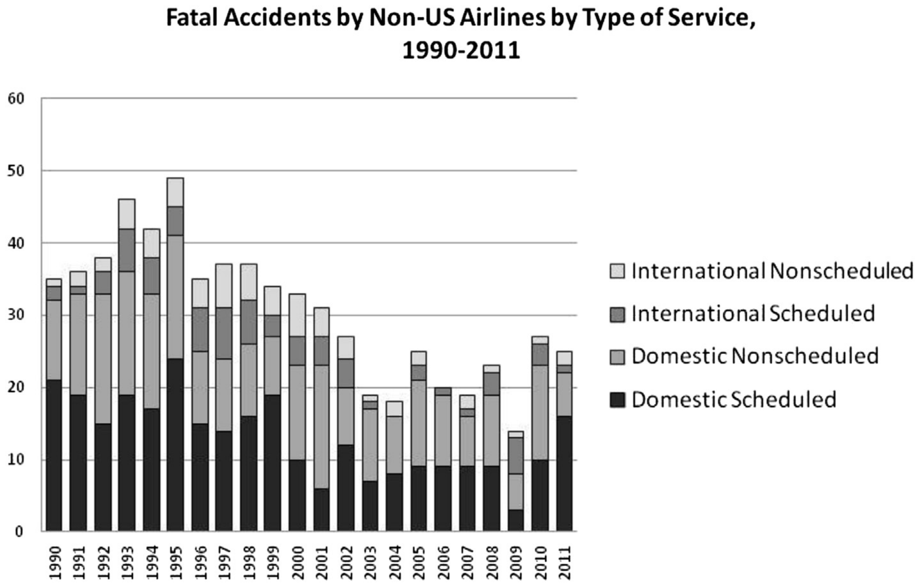

Fig. 1. Number of fatal accidents by type of service, 1990–2011. Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012).

reported operations data had, on average, safer operations than those that did not report data, but there is no way to know for sure.

An important question is how the safety of aviation operations varies across countries and regions of the world. Table 7 shows the fatality rates for domestic scheduled and international scheduled service by region. Again, because of incomplete enplanement data, some of these rates must be viewed with caution. As can be seen in the table, the share of the region's fatalities from accidents by carriers who report data to ICAO varies considerably by region. While these rates only reflect those carriers who report, it appears that both domestic and international service in South America and international service in Africa are likely much less safe than service in Western Europe.

Table 8 shows share of accidents and passenger fatalities by aircraft type. The aircraft types were defined as follows:

- Large jets – Those jet aircraft that in typical passenger configuration have more than 100 seats.
- Regional Jets (RJ)/Medium Jets – Those jet aircraft designed for commercial passenger service that in typical passenger configuration have 100 or fewer seats.
- Small Jets – Those small jet aircraft designed primarily for corporate or private use.
- Turboprops – All turboprop powered aircraft.
- Piston – All piston engine aircraft.

Not surprisingly, large jets account for two-thirds of passenger fatalities since they are most frequently used in scheduled domestic and international passenger service. Turboprop aircraft account for nearly half of fatal accidents and nearly one fourth of passenger fatalities. Piston engine aircraft account for nearly

Table 6
Fatalities and fatality rate for non-United States airlines by type of service, 1990–2011.

	Type of service			
	Domestic scheduled	International scheduled	Domestic nonscheduled	International nonscheduled
Total passenger fatalities	8482	5351	2326	1892
Fatalities per million enplanements	0.33	0.32	0.37	0.28
Share of fatalities included in fatality rate	41%	57%	3%	17%

Table 7
Fatality rates for non-United States airlines by region by type of service, 1990–2011.

Region	Domestic scheduled passenger		International scheduled passenger	
	Fatalities per million enplanements	Share of region's fatalities in fatality rate	Fatalities per million enplanements	Share of region's fatalities in fatality rate
Africa	0.20	3%	2.89	48%
Asia	0.26	45%	0.35	49%
Australia/Oceania	0.02	4%	0.00	0%
Canada	0.00	NA	0.00	NA
Central America/Caribbean	0.28	24%	0.53	76%
Eastern Europe/Former Soviet Union	0.67	32%	0.47	53%
Middle East/North Africa	0.66	31%	0.65	59%
South America	1.04	77%	0.86	66%
Western Europe	0.08	64%	0.15	68%
Overall	0.32	40%	0.32	57%

NA – Because there were no fatalities among carriers reporting operations, this measure is not meaningful. Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012) and ICAO Data – Airline Traffic Summary Reports.

Table 8
Accidents and passenger fatalities for non-United States airlines, by type of aircraft, 1990–2011.

Aircraft type	Number of accidents	Share of all accidents	Number of fatalities	Share of all fatalities	Average fatalities per accident
Large jet	157	25%	12,352	68%	79
Turboprop	287	46%	3816	21%	13
Regional/medium jet	33	5%	1007	6%	31
Piston engine	132	21%	787	4%	6
Small jet	19	3%	89	0.5%	5

Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012).

as many accidents as large jet aircraft, but because they are much smaller, account for only 5 percent of passenger fatalities. Unfortunately, the limitations in the enplanement and aircraft departure data prevent calculating fatality or fatal accident rates by aircraft type.

Table 9 breaks the fatality rates for domestic and international scheduled service into two periods: 1990–2006, and the last five years, 2007–2011. It is encouraging that the fatality rates in both segments appear to have improved in the last five years. It is also encouraging that more carriers are reporting enplanement data in the last five years than previously.

3.3.1. Accident causes outside of the United States

The authors examined accident reports for 629 commercial (scheduled and nonscheduled) aviation accidents in fixed-wing aircraft outside of the United States that resulted in at least one passenger fatality during the period 1990–2011. The source of the data was the World Aircraft Accident Summary (WAAS) – CAP 479, Issue 167, Ascend 2012, produced by Airclaims Limited. While incomplete operations data make it difficult to know how to interpret some of the fatality rates, it is possible to look at the causes of accidents and compare the mix of causes across different parts of the industry. Sequence-initiating causes were assigned to these accidents using the approach described earlier in the paper. The information about the accident presented in the WAAS data are drawn from multiple sources including official investigations and unofficial accounts including press reports. The information is not nearly as complete as that provided for U.S. accidents by the National Transportation Safety Board, and it may contain incorrect or even conflicting information. Because of the characteristics of these data and because many accidents in remote parts of the world are not investigated thoroughly, the authors were unable to assign a cause for 21 percent of the accidents. There was often less information about accidents in nonscheduled service than about accidents in scheduled service, so the proportion of accidents for which a cause could not be assigned was higher in the nonscheduled segments of the industry. Accidents for which causes could not be assigned are excluded from the distributions of causes presented below. In much of the world, cargo flights also carry small numbers of commercial passengers, so those cargo flights which carried passengers and were involved in crashes where at least one passenger was killed are included. However, the share of passengers killed on cargo flights is small.

Table 9
Fatality rates for non-United States airlines in scheduled service over time.

	Domestic scheduled		International scheduled	
	1990–2006	2007–2011	1990–2006	2007–2011
Fatality per million enplanements	0.38	0.21	0.35	0.27
Share of fatalities included in fatality rate	38%	53%	46%	99.6%

Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012) and ICAO Data – Airline traffic summary reports.

Table 10 shows the distribution of accident causes by type of service. For each type of service, pilot error is the most common accident cause, accounting for between 45 percent and 51 percent of accidents and equipment failure is the second most common, accounting for between 25 percent and 37 percent of accidents. While there is some variation in the shares of these causes across the types of service, the distributions are still quite similar and none of them is much different from the overall average.

Table 11 shows the distribution of accident causes by region. Pilot error is the most prevalent cause in almost all of the regions, but its share ranges from a low of 29 percent in Africa to a high of 61 percent in Central America and the Caribbean. In Africa, equipment failure was a more prevalent cause than pilot error and in Canada the two causes were equally prevalent. An earlier study applied the same methodology to assigning causes to accidents in the 1977 to 1989 period (Oster et al., 1992). While the earlier study didn't look at quite as full a range of airlines as formed the base for Table 11 and also used slightly different groupings of countries, it was very similar in its scope. A comparison of that study and Table 11 finds that the share of accidents attributed to pilot error increased in all of the regions between the 1977–1989 period and the 1990–2011 period.[11] Similarly, the share of accidents caused by equipment failure increased in most of the regions between the earlier and later periods. In contrast, the share of accidents attributed to weather decreased between the 1977–1989 and the 1990–2011 periods in all regions except Africa. Similarly, the share of accidents caused by terrorism, conflict, or criminal activity decreased in Africa, Asia, Western Europe, and the Middle East in the later period. Because safety has likely improved between the earlier period and the later one, this increase in the share of accidents caused by pilot error and equipment failure does not necessarily mean that pilots are causing crashes more frequently or that equipment is failing more frequently. But it does suggest that, at a minimum, more improvements have been made in reducing accidents caused by weather and by terrorism, than in reducing accidents caused by pilot error. It is also possible that the worldwide growth in aviation has resulted in less experienced or even less talented pilots flying in commercial service more often and in older aircraft being kept in service longer. These topics clearly warrant further research.

Table 12 shows the distribution of accident causes by type of aircraft. There are some noticeable differences across aircraft types. Pilot error is the most prevalent cause for each of these aircraft types. For large jet service pilot error accounts for 46 percent of accidents, for regional and medium jets it accounts for 57 percent, and for turboprops, it accounts for 49 percent. These are much higher shares of pilot error than the Part 121 service in the United States, where pilot error accounted for 27 percent of the accidents. Part 121 service in the United States is primarily large jet and regional/medium jet service, with some turboprop service. It is also notable in Table 12 that piston aircraft had the by far highest share

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[11] This comparison is based on information in Table 5.14 in Oster et al., 1992.

Table 10
Causes of accidents by type of service, non-United States airlines, 1990–2011.

Accident cause	Domestic scheduled	International scheduled	Domestic nonscheduled	International nonscheduled	All passenger service
Equipment	25%	29%	37%	28%	30%
Seatbelt/turbulence	0%	2%	0%	0%	0%
Weather	15%	10%	14%	15%	14%
Pilot error	51%	46%	45%	47%	48%
Air traffic control	1%	0%	1%	2%	1%
Ground/cabin crew	0%	5%	0%	0%	1%
Other aircraft	2%	3%	2%	4%	2%
Terrorism/conflict/criminal	4%	6%	2%	4%	4%
All causes	100%	100%	100%	100%	100%
Unknown cause/other	17%	7%	30%	18%	21%

Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012).

Table 11
Causes of accidents by region, non-United States airlines, 1990–2011.

Accident cause	Africa	Asia	Australia/ Oceania	Canada	Central America/ Caribbean	Eastern Europe/ Former Soviet Union	Middle East/ North Africa	South America	Western Europe	Total
Equipment	35%	28%	29%	38%	25%	23%	29%	34%	26%	29%
Seatbelt/turbulence	0%	0%	0%	0%	0%	0%	0%	0%	2%	0%
Weather	22%	8%	16%	19%	12%	15%	18%	11%	14%	14%
Pilot error	29%	58%	55%	38%	61%	49%	38%	46%	44%	48%
Air traffic control	3%	1%	0%	0%	0%	0%	0%	1%	2%	1%
Ground/cabin crew	1%	0%	0%	0%	0%	2%	0%	1%	2%	1%
Other aircraft	1%	0%	0%	5%	0%	2%	9%	4%	7%	2%
Terrorism/conflict/ criminal	8%	5%	0%	0%	2%	10%	6%	2%	2%	5%
All causes	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
Unknown cause/other	18%	23%	21%	34%	11%	6%	11%	32%	12%	20%
Passenger fatalities	2507	4860	376	389	732	2669	2547	2317	1629	18,026

Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012).

of equipment failure. Piston engines are more complex with more moving parts than jet or turboprop engines and often have fuel delivery systems more vulnerable to icing. Piston engine aircraft are also often operated by smaller carriers.

3.4. Improving the safety record

Overall, air travel in scheduled service appears to have been getting safer. The major jet airlines of Australia, Canada, New Zealand, Western Europe, and the United States have become extremely safe. Extensive accident investigations taking advantage of information in cockpit voice recorders and flight data recorders have improved understanding of the multiple factors that can contribute to an accident. Improved understanding of human factors and adoption and improvement in Safety Management Systems should lead to further improvements in safety in these already very safe segments of aviation.

However, other segments of commercial aviation, whether it be jet operations in some less developed regions of the world or nonscheduled service in turboprop, piston powered, or other smaller aircraft do not appear to operate as safely. Taken together, these segments account for substantial numbers of passenger fatalities. Improving safety in these segments of commercial aviation will be challenging. In many cases an absence of data on operations makes it difficult even to assess with confidence how safely these segments operate. Since the aircraft are typically smaller, each accident accounts for relatively few fatalities. As a result, the accident investigations (when there are formal investigations), typically are much less extensive and less is learned about exactly what caused the accident. Many of these accidents are also in remote areas where timely accident investigation can be especially difficult. Even where careful accident investigations are conducted, those investigations are limited by incomplete or unavailable flight data recorder data or cockpit voice recorder data.

Without more complete operations data to allow a careful identification of which segments of aviation pose the greatest safety hazards and without more extensive accident investigations

Table 12
Causes of accidents by type of aircraft, 1990–2011.

Accident cause	Large jet	Regional/medium jet	Small jet	Turboprop	Piston engine	Total
Equipment	25%	20%	15%	28%	46%	29%
Seatbelt/turbulence	1%	0%	0%	0%	0%	0%
Weather	12%	17%	15%	16%	10%	14%
Pilot error	46%	57%	62%	49%	43%	48%
Air traffic control	1%	0%	0%	1%	0%	1%
Ground/cabin crew	2%	0%	0%	0%	0%	1%
Other aircraft	4%	0%	8%	2%	0%	2%
Terrorism/conflict/criminal	10%	7%	0%	3%	1%	5%
All causes	100%	100%	100%	100%	100%	100%
Unknown cause/other	6%	9%	32%	22%	34%	20%

Source: Authors' calculations from World Aircraft Accident Summary (WAAS) data (Airclaims, 2012).

aided by information from flight data recorders and cockpit voice recorders, it will likely be difficult to make substantial improvements in the safety of these operations, much less bring their safety level up to that of the major scheduled jet airlines.

4. Aviation security as an aspect of aviation safety

When most people in the United States think of aviation terrorism and security, they think of the events of September 11, 2001 and the new security measures put in place since then. While some of the pre-boarding security procedures date from the September 11, 2001 hijackings, terrorist threats to aviation go back well over 60 years and pre-boarding security procedures in response to such threats go back nearly three decades. Concerns about vulnerabilities in the U.S. aviation security system predate 2001 (GAO, 1996). As seen above, from 1990 through 2011, terrorism, conflict, or other criminal activity was responsible for 15 percent of fatal Part 121 accidents and 1 percent of fatal Part 135 accidents in the United States, and 4 percent of fatal accidents in the rest of the world. In most of the world (and especially in the United States), it is virtually impossible to travel on a scheduled airline without being vividly reminded of the policy responses to potential terrorist threats.

4.1. Types of threats

There are four basic types of terrorist threats to the safety of aviation passengers:

- The first is the destruction of an aircraft, most commonly with a bomb but also with a missile or gunfire. Two of the most deadly terrorist acts against aviation were bombings. On June 23, 1985 a bomb exploded on an Air India 747 resulting in 329 fatalities. On December 21, 1988 a bomb exploded on a Pan Am 747 resulting in 259 fatalities aboard the aircraft and 11 fatalities on the ground. Aircraft destruction with missiles or gunfire is found most often as part of military activities or in countries subject to civil war or other conflicts.
- The second type of threat is the hijacking or takeover of an aircraft. In the past, these events have most often been undertaken either for some sort of hostage exchange or for escape from a country. As the events of September 11, 2001, showed, however, an aircraft can also be hijacked to be used as a weapon resulting in loss of life both aboard the aircraft and on the ground.
- The third type of terrorist threat to aviation is an attack on an airport to create destruction or loss of life. Fortunately, such attacks have not been nearly as common as bombings or hijackings, but notable events include the explosion of a bomb in a coin-operated locker at New York LaGuardia airport on December 29, 1975, the coordinated attacks on the Rome and Vienna airports on December 27, 1985, and the bombing attack on Moscow's Domodedovo airport on January 24, 2011. Attacks on the aviation system airports using chemical or biological weapons are also a potential threat (National Research Council, 2006).
- Finally, a fourth type of terrorist threat would be a disruption of the aviation system, perhaps through disabling or tampering with air traffic control systems (GAO, 2000).

4.2. Bombings

Aircraft bombings are not a recent phenomenon. The first aircraft destroyed by a bomb was a United Airlines Boeing 247D which crashed in Indiana in 1933 as a result of a nitroglycerin bomb exploding in the luggage compartment (NYC Aviation, 2012). Fig. 2 shows the number of worldwide bombings of aircraft in five year increments for the period 1960 through 2011. Note that the last column in the figure represents seven years while the other columns represent five years. During this period, there were 74 bombings of aircraft which killed 2068 people aboard aircraft. Bombings are not always successful in bringing down an aircraft or in killing those on board. In 37 of the 74 bombing events (50 percent), no one was killed and in another 7 events (9 percent) only a single person was killed. Bombings can also result in large loss of life. Seven of the eight terrorist events with the largest on board loss of life were bombings, all of which occurred between 1983 and 1989.

In response to the bomb in an airport locker at LaGuardia on December 29, 1975, the FAA increased its efforts to develop explosives detection equipment, which could be used to detect bombs in checked luggage. After testing early versions of a Thermal Neutron Activation (TNA), FAA began testing a prototype system at the San Francisco airport in 1987 and on November 7, 1988, FAA announced the award of a contract for five operational models of a TNA system. On December 19, 1987, the FAA also required positive passenger bag matching wherein if the passenger who checked the bag does not get on the plane, the bag is removed unless that bag had been physically searched on all international flights by U.S. airlines. FAA had required such positive passenger bag matching on selected international flights starting in the summer of 1985 (FAA, 2008).

On December 21, 1988, Pan Am flight 103 was blown up over Lockerbie, Scotland by a bomb using a plastic explosive (Semtex) placed in a radio/cassette player packed in a suitcase. Shortly after the bombing, FAA announced new security measures for U.S. carriers at all airports in Europe and the Middle East including that airlines X-ray or physically search all checked baggage and that they achieve a positive match of passengers and their baggage. FAA also ordered an additional TNA system (FAA, 2008).

A presidential commission appointed to review the circumstances surrounding Pan Am 103 issued their report on May 15, 1990. On the first page of the Executive Summary, the report stated that, "The Commission found the FAA to be a reactive agency — preoccupied with responses to events to the exclusion of adequate contingency planning in anticipation of future threats" (President's Commission on Aviation Security and Terrorism, 1990, p. i). As will be seen, this problem continues to plague the United States responses to aviation terrorism. The Commission was unable to determine precisely how the bag containing the bomb got on the

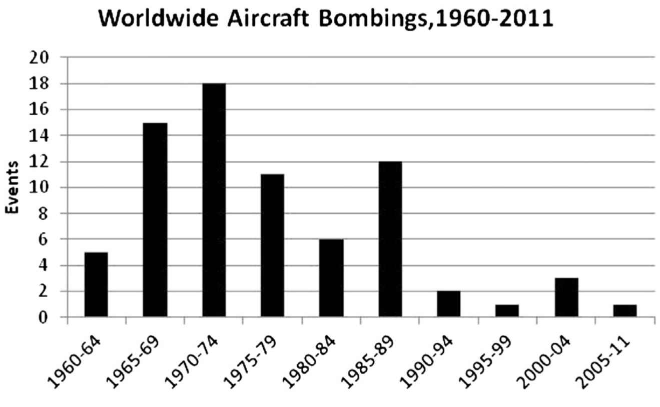

Fig. 2. Worldwide aircraft bombings, 1960 through 2011. Source: Authors compilation based on data from the Aviation Safety Network database (Flight Safety Foundation, 2012).

plane, but faulted Pan Am for not having stricter baggage reconciliation procedures in their bag matching process procedures and for not having adequate security for baggage containers at airports. Pan Am was X-raying bags rather than reconciling them with passenger lists or physically searching them, but the X-ray procedures used at the time could not reliably detect Semtex. However, the Commission also pointed out that TNA, which the FAA was vigorously pursuing to be expanded to 40 international airports was not capable of detecting that amount of explosive in this bomb, so even if TNA had been available and used on this bag, the explosives would have not been detected (President's Commission on Aviation Security and Terrorism, 1990, p. iv). The Commission recommended deferring the FAA's planned program of requiring U.S. carriers to purchase and deploy TNA machines and instead pursue research in to more effective technologies.

As Fig. 2 shows, the number of bombing events dropped sharply after 1989. The policy responses to three more recent bombing events, all after September 11, 2001, reflect a reactive approach in that they are very narrowly directed to prevent a recurrence of the same type of event along the lines that the Commission had criticized. The first started on December 21, 2001 when a passenger unsuccessfully attempted to light a fuse that was intended to detonate explosives concealed in his shoe on a flight from Paris, France to Miami. The previous day he had been prevented from boarding because he had paid cash, had no luggage, had no fixed address, and had no firm travel plans. However, after questioning by French police he was allowed to travel the next day. The policy response was to require passengers to remove their shoes and put them through the x-ray machines designed for carry-on baggage.

The second event was in 2006, when British police arrested 24 people who were suspected of a plot to detonate liquid explosives carried on board at least 10 commercial aircraft traveling from the United Kingdom to the United States and Canada. This plan was reminiscent of a 1995 plan to use bombs to destroy 12 U.S. aircraft flying in East Asia during a 48 h period that was discovered and stopped before it could be implemented (FAA, 2008). The 2006 plan was to carry the components of the bombs, including liquid explosive ingredients, and assemble and detonate the bombs while in flight (McCullagh, 2006). The policy response to this event was to limit carryon containers of liquids or gels to no larger than 3 ounces; to limit the number of containers to those which would fit in a quart-size bag; and to limit each traveler to one quart size bag (Transportation Security Administration, 2012). As with the response to the 2001 shoe-bomb incident, this response was again narrowly targeted at preventing this specific type of event, but this response was by the Transportation Security Administration (TSA) which had taken over the responsibility for aviation security from the FAA in February 2002 and been made part of the Department of Homeland Security in November 2002.

On December 25, 2009, a passenger attempted to detonate explosives he had concealed in his underwear on a flight from Amsterdam to Detroit. Passengers intervened and the explosives did not fully detonate. This passenger was allowed to board despite having purchased his one-way ticket with cash and not being in possession of his own passport. Moreover, the previous month his father had contacted the U.S. Embassy with concerns about his son's behavior and his name was then added to the Terrorist Identities database of the U.S. National Counterterrorism Center. The policy response has been the installation of full body scanners at most airports. Such scanners have the potential to detect explosives hidden under a passenger's clothing. The use of such scanners has raised both privacy and health concerns. Once again, the response was reactive and narrowly designed.

4.3. Hijackings prior to 2001

Hijackings present a much different sort of threat than bombs on aircraft and are also not a recent phenomenon. While there had been hijackings of non-commercial aircraft earlier, it appears that the first hijacking of a commercial passenger aircraft was on July 16, 1948, when during a failed attempt to gain control of a Cathay Pacific seaplane it crashed into the sea (Military History Encyclopedia on the Web, 2012). Fig. 3 shows the number of hijacking events worldwide from 1960 through 2011. In both the United States and the rest of the world, hijackings jumped in 1968 and then increased even more sharply in 1969 with most of the hijacked planes flown to Cuba. Indeed, 31 of the 39 hijacked U.S. planes that year went to Cuba as did 25 hijacked foreign airline planes In response, FAA created a Task Force on the Deterrence of Air Piracy which found that using a hijacker profile based on the behavioral characteristics of past hijackers combined with a magnetometer FAA had developed to detect firearms was promising. The system was tested by Eastern Airlines starting in October, 1969 and adopted by three other airlines by June, 1970. The system was implemented at New Orleans International Airport in July 1970. Hijackings continued, however, and in December 1972, FAA issued a rule that required carriers to inspect all carry-on baggage for weapons and scan each passenger with a metal detector, or conduct a physical search, prior to boarding starting on January 5, 1973 (FAA, 2008). Whereas the test programs had applied only to passengers fitting a profile, this rule applied to every passenger. As is evident in the figure, hijackings dropped dramatically following the implementation of this rule. Also, on February 15, 1973, the United States and Cuba signed an anti-hijacking agreement, which lasted until Cuba abrogated the agreement on October 15, 1976 (FAA, 2012c). The spike in U.S. hijackings in 1980 was largely the result of Cubans who came to the U.S. during the Mariel boatlift, which started in April 1980, hijacking planes to return to Cuba.

4.4. September 11, 2001

By the late 1980s, the hijacking problem for U.S. airlines had largely subsided, although hijackings remained common throughout the 1990s in the rest of the world. There were still concerns in the United States about terrorist threats to aviation and recognized weaknesses in the aviation security system, but some feared the decline in events involving U.S. airlines may have resulted in some complacency (GAO, 2000). Then, on the morning of September 11, 2001 four U.S. aircraft were hijacked. Two aircraft

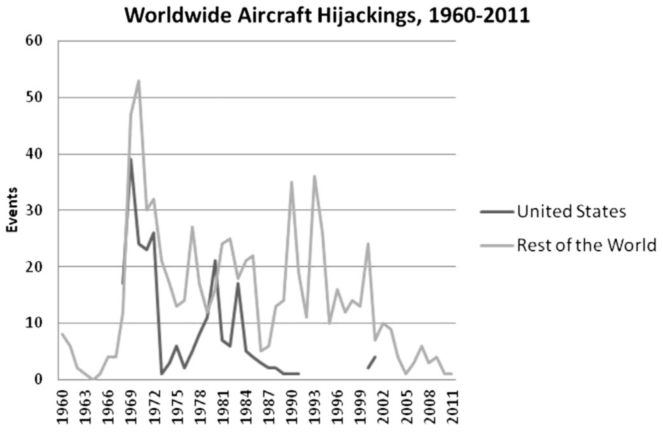

Fig. 3. Worldwide aircraft hijackings, 1960–2010. Source: Authors compilation based on data from the Aviation Safety Network database (Flight Safety Foundation, 2012).

were crashed into the twin towers of the World Trade Center in New York City. A third aircraft crashed into the Pentagon in Washington, D.C. The final aircraft crashed in a field near Shanksville, Pennsylvania as the passengers tried to regain control of the aircraft from the hijackers. These hijackings have had a large impact on U.S. aviation security policy and on the passenger flying experience so it's worth looking briefly at how they happened and what the policy responses have been.

The September 11 hijackings exploited three important characteristics of the U.S. aviation security system at the time. First, the hijackers did not challenge the passenger screening system. The passenger screening system was designed to prevent firearms and bombs from being brought on board. The hijackers did not use firearms as weapons but instead used box cutters, a common form of cutting instrument that was permitted to be brought on board aircraft under the rules in force at the time. Indeed at the time even much larger knives than the box cutters were permitted, so the hijackers did not push the permissible size limit on the weapons they used. The hijackers also did not bring explosives on board, but hijacked aircraft heavily loaded with fuel to serve as the explosive.

Second, the hijackers did not challenge the training of the flight crews. Between 1960 and 2000, there were 817 hijackings worldwide. There were no fatalities in 87 percent of these hijackings and only one fatality in another 8 percent. The vast majority of prior hijackings had as their goal either allowing the hijacker to escape to another country or holding the plane and its passengers as hostage to be exchanged for the release of political or other prisoners. When confronted with a hijacking attempt, flight crews were trained not to resist the hijackers but instead to follow the hijackers' instructions and get the plane safely on the ground where negotiations could take place. Only because some of the passengers on the fourth flight discovered what was happening from phone calls, did those passengers try to retake the plane thus resulting in crashing in a Pennsylvania field rather than the hijackers' intended target.

Third, the hijackers did not challenge military training. The military was not trained for, nor prepared to, intercept and shoot down civilian airliners in congested airspace over heavily populated areas. There were only 5 min between the air traffic control determination that the first flight had been hijacked and when that flight struck the World Trade Center. Two fighters jets were scrambled from an air force base 150 miles from New York City 1 min after the first plane had struck the World Trade Center. However, there was only 16 min before the second plane would hit the second tower, and even then, the fighter jet pilots did not know where the hijacked aircraft was that they were trying to intercept in part because the hijackers had turned off the aircraft's location transponder (The 9/11 Commission, 2004).

There were several quick and visible policy responses to the September 11 hijackings. One was to require that cockpit doors be reinforced so that hijackers could not easily gain access to the flight deck. Another was to add box cutters, knives, and razor-type blades to the list of items that could not be brought on board aircraft. A third was to replace private contract screeners with federal employee screeners even though no breakdowns in the screening process had contributed to the September 11 hijackings. A fourth response was to transfer the responsibility of aviation security from the FAA to a newly created agency, the TSA. The first two responses were narrowly focused to prevent a recurrence of this exact type of event. The effectiveness of the last two responses on improving aviation safety is not clear.

4.5. *Challenges to improving aviation security*

While it may be popular to criticize the TSA and the Department of Homeland Security, it is important to recognize the challenges associated with improving aviation security. One challenge is how much to focus on identifying the terrorists themselves and how much to focus on identifying the tools they might use. Even a casual look at the people who have been identified as committing terrorist attacks on aviation often share some age, gender, and other background characteristics. While it is possible that future terrorists will not share these characteristics, one approach would be to use the characteristics of past terrorists to try to identify future terrorists. In the United States, such an approach has met with resistance that it amounts to profiling, so the tendency has been to apply security procedures equally to all passengers. The TSA has developed and has begun implementing a program called Screening Passengers by Observational Techniques (SPOT) to identify suspicious passengers at U.S. airports. Challenges have been encountered by TSA as it strives to validate the approach on a scientific basis and evaluate the program's success (GAO, 2010b).

A second approach is to focus on detecting the tools a terrorist might use and prevent these tools from being brought on board or used in an airport environment. This approach involves explosives detection equipment to prevent bombs on checked luggage, cargo, carry-on luggage, or concealed on the passenger as well as other detection equipment to prevent weapons from being brought on board. It also involves improving airport perimeter security and access controls (GAO, 2007). Clearly these approaches are not mutually exclusive.

A second challenge is deciding what to tell the public. One approach is to be completely forthcoming and tell the public everything that is being done and why and to reveal what terrorist efforts have been stopped and how. Such an approach likely enhances credibility among the public, but it also provides valuable information to prospective terrorists. Conversely, if such information is not provided, terrorists are not helped, but transparency is sacrificed negatively affecting credibility with the public. A related challenge is what threats to respond to - the threats judged to be greatest by aviation security analysts or what the public perceives as the greatest threats. Most of the aviation security policies so far seem to have been directed at the greatest perceived threats, as determined by events that have already happened.

A third challenge is how much to respond to terrorist threats. Unfortunately, there is a clear tradeoff between potential harm from terrorist activities and actual harm from steps taken to prevent these activities. That actual harm comes in the form of the added cost and inconvenience of air travel. One estimate was that in 2007, the recurring capital and operating costs for aviation security were in the range of \$10–15 billion and the delay costs to travelers were on the order of an additional \$13–24 billion with the expectation that costs were likely to increase in the future (Oster & Strong, 2008a). Security measures have clearly increased the cost of air travel relative to travel by automobile, measured both in terms of time cost and out of pocket cost. There seems little doubt that added air security costs have caused some people to shift from air travel to auto travel, particularly for short-haul trips. Because air travel is much safer than highway travel, such shifts cause more transportation deaths. More generally, it is extremely difficult to measure the benefits of aviation security policies (Jackson et al., 2012). Adding to the measurement difficulties is the fact that one of the goals of aviation security policy is to deter prospective terrorists, but it is virtually impossible to measure how much deterrence has been achieved. Attempts to measure the cost-effectiveness of aviation security measures have found that estimating the lives saved from any specific measure can require some very strong assumptions (Stewart & Mueller, 2008).

A fourth challenge is that aviation security risks are dynamic but policy responses can take time to develop and implement, particularly in an aviation system with over 550 commercial service airports[12] (GAO, 2011b). Consider, for example, the issue of explosives detection equipment. In 2005, TSA developed requirements for explosives detection equipment (GAO, 2011a). It took until 2009 for TSA to begin deploying equipment that met these standards. Then in January 2010, TSA revised the explosives detection requirements to address current threats with respect to physical characteristics and minimum masses that could be detected. More generally, the tactics used by terrorists in past attacks will not necessarily be those used in future attacks so in addition to reducing vulnerabilities revealed by past attacks, successful security policy must address potential weaknesses before they can be exploited.

A fifth challenge is determining the public versus private roles in providing aviation security. There are both advantages and disadvantages in having the federal government providing aviation security as is done in the United States as opposed to using some sort of public–private partnership as is most often done in Europe (Coughlin, Cohen, & Khan, 2008). A related challenge is that with current policy in the United States, the TSA is both the provider of aviation security services, and the regulator of such services. In essence, TSA regulates itself. Such self-regulation has been shown repeatedly to create problems in many sectors, including aviation (Oster & Strong, 2008b).

Aviation security is an important part of aviation safety, but it differs from other aviation safety issues. Improving aviation security involves thwarting attempts by individuals to disrupt, damage, or destroy parts of the aviation system intentionally. Improving other aspects of aviation safety involves reducing the chances that unintentional mistakes or unexpected failures of parts of the system will reduce the safety of air travel.

5. Emerging issues and challenges in aviation safety

5.1. *Maintaining and improving the (excellent) aviation safety record*

Commercial aviation has experienced remarkable improvements in safety since its inception. This performance is even more noteworthy given the dramatic worldwide growth in the industry, spurred by new technologies, by deregulation/liberalization/privatization, and by global economic development. This record is also the result of a joint and concerted effort over many years by industry stakeholders, from aircraft and engine manufacturers, to airlines, to governments and regulatory bodies (Rodrigues & Cusick, 2012).

The challenge of maintaining this performance is ongoing and demanding. Many major improvements in safety have come from concerted efforts on specific problems, leading to technology-supported solutions. For example, accidents involving controlled flights into terrain and increased risk from near misses in congested airspace have been substantially mitigated by the development and adoption of ground proximity warning systems and by collision avoidance systems, which not only identify impending safety risks, but also help flight crew manage them. Improvements in communications, navigation, and surveillance technologies and better on-board weather information have helped airlines be aware of and avoid or reduce flight safety risks.

At the same time, new challenges are becoming apparent. The new generation of airframes makes extensive use of composite materials, which require different maintenance and inspection procedures than the aluminum that was previously used. The development of larger aircraft and longer ranges place new demands for reliability and performance. The widespread adoption of regional jets beginning in the 1990s now presents new challenges as these aircraft age. All three are representative of issues that have arisen and will need to be managed to maintain the overall safety record.

A major initiative to improve safety is the increasing role of Safety Management Systems (SMS), intended as "an organized approach to managing safety, including the necessary organizational structures, accountabilities, policies, and procedures" (ICAO, 2012). ICAO has championed this initiative, which is now included in international standards for airline operations (ICAO, 2009). The basic structure involves four "pillars": identifying safety hazards; safety risk management through remedial actions to address safety risks; continuous monitoring and assessment of the safety level sought and achieved; and programs for continuous improvement in the overall level of safety. Following ICAO's introduction of SMS into worldwide aviation, the FAA initiated voluntary SMS pilot projects and implementation in 2007. This program was accelerated in the wake of the Colgan Airlines crash in February 2009, with legislation mandating the FAA move forward with SMS on an expedited basis.

The main idea is that further improvements in safety will increasingly come from proactive approaches that identify and mitigate risks before incidents or accidents occur. Regulators will have to assess and monitor the programs and systems in place as well as conduct more traditional specific inspection and investigation activities. In effect, a combination of quality and auditing principles are being applied in the hope that safety management will become more predictive when it comes to safety risks.

5.2. *Extending safety to other segments of commercial aviation*

Another challenge is how to extend the safety record of the large airlines to other, less safe, segments of commercial aviation. Two segments of global aviation are particularly important – the safety performance of airlines in less developed, often rapidly growing countries and regions, and the safety performance of smaller commercial operations such as air taxis and nonscheduled operations.

Improving the international safety records in developing countries has many different aspects. In some cases, problems occur because of older, poorly maintained equipment and limited regulatory enforcement. Other problems can arise from inadequate infrastructure and less effective flight crew training.

In both the international and in the smaller commercial aviation settings, there are data challenges to understanding and improving safety performance. One challenge is that an absence of operations data makes it extremely difficult to measure the safety levels of these various industry segments. Without being able to do that, one cannot identify with any certainty which segments have the largest safety problems. In many of these segments, the level of safety is likely comparable to that of the large airlines many years or decades ago. So for some of these segments, the reactive approach of focusing on why accidents happened and looking for patterns of causes would still likely pay large dividends in targeting efforts to improve safety.[13] A second challenge is improving the quality of accident information and investigations.

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[12] Commercial service airports are those that enplane over 2500 passengers per year. http://www.faa.gov/airports/planning_capacity/passenger_allcargo_stats/passenger/media/prelim_cy11_npcs_enplanements.pdf.

[13] There is also still a role for detailed investigations of accidents involving the largest and best established airlines as the lessons learned from the 2009 crash of Air France flight 447 illustrate.

5.3. Runway incursions

As flight operations become safer, more attention needs to be paid to safety risks from aviation infrastructure, especially airport and runway operations and air navigation. These issues are becoming more important as aviation growth puts strains on capacity and on the ability to manage congestion on the ground and in the skies.

Runway incursions are the principal airline safety risk on the ground. An incursion is defined as the incorrect presence of an aircraft, vehicle, or person on an area designated for take-offs or landings. Although runway incursion rates are quite low, the number of incursions has risen and has garnered renewed attention in recent years.

The FAA National Runway Safety Plan 2009–2011 reports that the rate of runway incursions at FAA-towered airports remained steady from 2004 to 2008. However, there were 1353 incursions during this four-year period. While the majority (92 percent) involved little or no risk of collision, the remaining eight percent were classified as serious events in which there “was significant potential for collision” or where “a collision was narrowly avoided” (FAA, 2009, p. 27).

As noted by Rodrigues and Cusick (2012), “The reasons for these significant problems are varied and complex but can be boiled down to human error in a challenging and confusing environment”. About two-thirds (66 percent) of the runway incursions were found to be caused by pilot deviations from directions or operational procedures; 18 percent from vehicle or pedestrian deviations onto active runways; and sixteen percent from air traffic control operational errors.

Reducing the frequency and risk of runway incursions requires provision of more consistent information about the airport surface environment. These improvements often involve better signage, traffic flows, and visibility. Other aspects include better communication procedures to avoid misunderstandings and to improve situational awareness. Since runway incursions by definition involve human error, research should continue to focus on the tasks that have the greatest potential to cause errors. At the same time, there is the opportunity to manage control strategies to minimize the probability that incursions occur, such as restrictions on ramp operations or expansion of surface radar technologies for better awareness in low visibility conditions. Such technology developments include airport surface detection systems, runway status lights, and ground surveillance systems. In addition, because each airport is unique, there is a need for localized airport solutions through runway incursion planning teams.

5.4. Human factors in aviation safety

As aircraft have become more reliable and navigation, landing aids, and weather forecasting have improved, an increasing share of aviation accidents and incidents appear to be initiated by human errors. Accident and incident research indicates that if even a portion of human factors issues that lead to these errors could be resolved, substantial reductions in accident risk can be achieved.

As aviation technology has improved, it has changed some of the roles and requirements for flight crews-which have introduced new risk factors. New concerns have emerged, such as a fear that increased cockpit automation will reduce flying skills so pilots are less prepared to react properly in the event of the failure or degradation of automated systems. Other examples include problems in crew coordination and resource management, man–machine interface issues such as the lack of cockpit standardization and basic problems in communication in the cockpit and between flight crews and air traffic controllers. In addition, major changes in air traffic control technology are being implemented, raising new issues of how to handle failures, both on the ground and in the cockpit, in increasingly automated systems.

Human factors research focuses on two main areas – cognitive and physical capabilities, and the interaction of people with technology. Unlike other aspects of aviation safety, human factors analysis does not always lend itself to consistent and precise measurements, and typically requires more time and cooperation than other types of safety research. However, significant progress has been made in applying lessons from human factors research, especially in crew resource management, line safety audits, and threat and error management.

5.5. Improving and extending data analytics

Aviation safety analysis historically has emphasized accident data. For the most part, the aviation industry and government regulators have used data reactively to identify the causes of airline accidents and to take steps to prevent these types of accidents from recurring. There is still a role for careful accident investigation and there are still lessons to be learned from the few accidents that these carriers have. But with improvements in safety and major reductions in accidents, airline safety analysis will have to shift toward analysis of incident and operational data with the intent of identifying safety risks before accidents occur.

There are two potential benefits from looking at these types of data. One is to address the question of why some sequences of events result in accidents while other sequences do not result in accidents. A better understanding of how potential accidents were avoided in some situations may lead to more such avoidances in the future. A second potential benefit is to identify trends in or the emergence of potentially hazardous sequences of events before they result in an accident. Here again, by identifying such trends, it may be possible to take corrective action before an accident occurs.

How do you get the necessary data to do these kinds of analyses? One way is to routinely collect such data automatically through flight data recorders. This is the approach taken with the FAA’s Flight Operational Quality Assurance (FOQA) program (FAA, 2012d). However, with this program, the data are collected and analyzed by the participating airlines with only limited amounts given to the FAA for additional analysis (GAO, 2010a). A second way is for pilots and other airline employees to report situations that are believed to be hazardous but do not result in an accident. This is the approach taken with the Aviation Safety Action Program (ASAP) (FAA, 2012b).

While programs like these hold promise, there are some clear challenges to getting the full potential benefits from them. First, the data must be consistently recorded and processed in such a way to allow integration with other data sets and analysis by a variety of analysts. A second challenge is that the data from these two programs lack some identifying details that are needed for some types of analysis and the data are only retained for three years. Overcoming these limitations will require addressing issues of confidentiality and concerns that by reporting such events one might be subject to disciplinary or regulatory actions. A third challenge is protection of safety information so that voluntary reporting can be extended, while balancing concerns for immunity, transparency, and accountability. A fourth challenge is ensuring enough researchers are analyzing the data. Given the tight budgets both the airlines and FAA face, it makes sense to broaden access so academic researchers can analyze the data, as long as confidentiality concerns can be resolved.

6. Summary and conclusions

Commercial airline safety has improved dramatically since the industry's birth over a century ago. Fatal accident rates have fallen to the level where (along many dimensions) aviation is now the safest mode of commercial transportation. The next generation of safety challenges now require development and understanding new forms of data, and moving from a reactive, incident-based approach toward a more proactive, predictive and systems-based approach.

Appendix A. Definitions of accident causes major categories

Equipment Failure: This category includes the failure of engines, instruments, electrical systems, landing gear or tires, and failure of any part of the structure of the aircraft including control surfaces. This cause category contains seven sub-categories.

Seatbelt Not Fastened/Turbulence: This category is to be used when a passenger death results from not having his or her seatbelt fastened when turbulence is encountered and adequate warning had been given by the flight crew. It is also used when a passenger is killed by turbulence when the seatbelt sign is not turned on and when the seatbelt sign is turned on but the passenger is killed before or while returning to his or her seat. Accidents caused by damage to an aircraft from turbulence would also be in this category. This cause category contains two sub-categories.

Environment/Weather: This category includes weather-related accidents resulting from wind shear, slippery runway (unless the pilot lands excessively long), emergency landings due to weather, and icing as well as other hazardous characteristics of the flight environment. Downdrafts in mountainous terrain are considered weather if altitude is 1000 above ground level. The category also includes accidents resulting from encountering high winds while the aircraft is on the ground (taxi, landing roll, takeoff roll, parked). It includes collision with any animals in-flight or on the ground. It also includes accidents due to evasive maneuvers trying to avoid animals. Finally, it includes any accident where the cause was an unseen obstruction or flaw in a non-paved runway. Examples would include hitting a submerged log with a float plane or breaking through the ice while landing on a river or lake. This category is also used for failures in runway lighting during touchdown and landing. This cause category contains four sub-categories.

Pilot Error: This category includes accidents resulting from deficiencies on the part of the pilot in maintaining physical control of the aircraft including flying an unstabilized approach. It also includes controlled flight into terrain (CFIT) accidents. The category also includes accidents caused by errors in pilot judgment both in-flight errors such as failure to do the landing and on-ground judgment such as takeoff for a VFR flight into marginal weather or takeoff into adverse weather or wind conditions. This also includes failure to determine the proper weight and balance and failure to ensure that cargo is secured prior to takeoff. It includes all running out of fuel in flight except for mechanical failures such as leaks and/or defective fuel cells. This cause category contains nine sub-categories.

Air Traffic Control: This category includes accidents precipitated by errors by controllers in Air Route Traffic Control Centers, Terminal Area Control Centers, and Towers as well as errors by personnel at Flight Service Stations. It also includes CFIT accidents caused by ground-based navigational equipment errors or malfunctions and accidents caused by evasive maneuvers commanded by TCAS. This cause category contains five sub-categories.

Ground/Cabin Crew: This category includes any accidents from errors by ground crew personnel employed by an airline and by ground crew or other ground-based personnel employed non-airline companies such as drivers of catering and fuel trucks. It also includes accidents caused by cabin crew error. This cause category contains three sub-categories.

Other Aircraft: This category includes any accident where two planes collide and either of the planes is in the air as well as any accident when two moving planes collide on the ground. This cause category contains two sub-categories.

Terrorism/Conflict/Criminal Activity: This category includes accidents caused by hijacking, bombings, missiles or gunfire as well as those resulting from other criminal activity. This cause category contains five sub-categories.

Unknown Cause/Other: This category includes accidents where the accident investigation was not able to determine the sequence of events in sufficient detail to determine the cause of the accident and accidents where the aircraft was not found or recovered and an accident investigation could not be done. It also includes other situations including when the pilot was medically impaired, when the flight was transporting illegal drugs, and where the pilot did not have a valid license. This cause category contains seven sub-categories.

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