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FINAL REPORT

RECOMMENDATIONS FOR INJURY PREVENTION IN TRANSPORT AVIATION ACCIDENTS

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EXECUTIVE SUMMARY

This report presents the results from a study of injury mechanisms in transport-category aircraft accidents. The purpose of the study was to use the identified injury mechanisms to develop recommendations regarding which crash safety technologies will provide the most benefit for reducing air transport fatalities. A combined approach of a database review and detailed case studies was utilized. Eleven partially survivable accidents occurring between 1985 and 1994 were reviewed in detail. The outcome of the case study review included a list of life-saving technologies and recommended actions for the implementation of these technologies.

Occupant protection in an aircraft crash, or any type of transportation-related crash, requires a system of protection. The system begins with the structure that surrounds the occupant. Fatalities in most of the cases studied can be directly related to loss of the protective structure around the occupant either through direct loss of occupiable space from intruding structures or from the subsequent loss of restraint as a result of failure of fuselage and floor structures. In the long run, the largest potential for protecting occupants in aircraft crashes is to improve the structural crashworthiness of transport aircraft.

The second required component of the occupant protection system is the restraint of the occupant within the structure. Occupant restraint involves the full set of links from the fuselage to the floor to the seat to the occupant. Any failure of this tie-down chain will lead to loss of occupant restraint and the potential loss of human life. In the cases studied, failures of the restraint linkage were predominantly related to the floor-to-seat connection. In accidents with high decelerative forces, or in areas of fuselage structural damage, the floor failed to maintain structural integrity. When floor failure occurred, passengers and seats tumbled forward together, producing serious and fatal crushing injuries. Alternative loading paths and improved resistance to out-of-plane loading should be pursued. When the floor remained relatively intact, seat restraint to the floor was often lost. Most of the seats studied were certified to a 9-G static test standard. Currently, newly type-certificated aircraft are required to meet a dynamic 16-G certification. The second critical improvement in restraint is to require the retrofit of seats qualified to the 16-G structural test requirements for all of the aircraft fleet.

The third required component of the occupant protection system is the management of energy transferred to the occupant. This means that any impacts or decelerative loading to which the occupant is exposed must be tolerated without fatally injuring the passenger or prohibiting their ability to affect their own rescue. There were two critical actions identified in this area. The first is to research the mechanisms of injury to the lower extremities when 16-G dynamic seats are used. Observed lower-extremity injury mechanisms are not captured by current testing protocols. If these mechanisms are not understood and corrected, they could substantially reduce the benefits of the new seating systems, as severe lower-extremity injury prevents passengers from egressing the aircraft under their own power. The second critical recommendation is to require that overhead baggage bins meet at least a 16-G dynamic performance requirement. Overhead bin attachments failed even in the more benign accidents reviewed, producing head and torso injuries.

The final component of the occupant protection system is the mechanism for egress and post-crash survival. When a fire occurs with the crash event, smoke inhalation can fatally injure many occupants who have survived the impact but have had insufficient time to egress the aircraft. Fire and smoke are the largest of the post-impact dangers and are probably also the most serious complication to passenger egress. Continued research in fire suppression,

reduced flammability and toxicity of materials, fuel system crashworthiness, and operational issues surrounding effective passenger egress are all high priority.

The combination of man with machine and the increased pressures on air travel systems will make it very likely that accidents will continue to happen. Accident avoidance and improved crash safety must work together to decrease both the fatal accident rate and to decrease the number of fatalities when an accident does occur. This report provides a description of a number of technologies and activities that, when implemented, can both increase the range of survivable accidents and can increase occupant survivability when an accident does occur.

1. INTRODUCTION

In 1996, the Gore Commission established the national objective of reducing the fatal aviation accident rate by 80 pct within 10 years. The FAA has established additional performance measures to help meet this target: reduction of the overall accident rate, reduction of fatalities and losses by type of accident, and reduction in occupant risk. To meet this aggressive target, consideration must be given on how to decrease the likelihood of an accident and how to decrease the severity of the accident through crashworthy features and occupant protection systems. In other words, there is a need to decrease the rate of fatal accidents by decreasing the number of accidents in general, and by decreasing the number of accidents which lead to fatalities.

In the transport arena, relatively few accidents occur per year. In 1998, the U.S. fleet logged a record number of passenger miles without experiencing a single fatality. To prevent accidents from occurring, efforts are being made in to identify, track, and mitigate the pre-cursors to an accident. However, the combination of people with machinery will inevitably lead a few accidents. The challenge thus becomes how to expand the realm of survivable accidents.

Before considering what can be done to improve survivability, it is important to consider what is necessary for survival:

1. **Occupiable Space** - If sufficient space is not maintained in an accident, the occupant will be crushed by intruding structures. For example, in racing cars, occupants have survived crashes of up to 100 G (Reference 1). However, the structure of the racing car's cockpit is built to withstand severe impacts without substantial deformation. Maintaining a livable volume is the first step in providing occupant protection.

2. **Occupant Restraint** - If the surrounding structure provides a livable volume for the occupant, the occupant must then be restrained within that livable volume and be prevented from impacting interior structure (secondary impact). In a transport aircraft, this means that the chain of linkages securing the occupant to the aircraft structure must be maintained. These linkages include the integrity of the aircraft fuselage and floor, the attachment of the aircraft seat to the floor track, and the restraint of the occupant in the seat.

3. **Energy Management** - Loads transferred to the occupant must be within human tolerance limits. Currently in transport aircraft, the limits of human tolerance are substantially greater than the aircraft's design limits. Recent work with racing cars demonstrates that the level of human tolerance to impact may well be close to 100 G if the occupant is effectively restrained. This is in contrast to current transport aircraft, in which the seats are designed to withstand only 16 G. Energy transferred to the occupant can be managed through such systems as energy-absorbing seats, improved restraint systems, and delethalized interiors.

   In addition, the environment inside the livable volume should not be injurious. The potential for injurious interaction with interior strike hazards should be minimized and exposure to other hazards eliminated. For commercial aircraft, passenger strike hazards include the seat in front of the passenger; the fuselage structure; interior items such as galleys, lavatories, bulkheads; any debris that might enter the area; and any deployable items (e.g., tray tables, etc.). The risk of injury from these hazards should be minimized.

Due to hazards in the post-crash environment, energy management often must include the retention of the ability to egress the aircraft, and not only the maintenance of life during the impact sequence.

4. **Egress and Post-crash Survival** - Often following an impact, the presence of fire, smoke, water, or other hazards increase the risk to the occupants. Once the occupant has survived the impact, they must be able to egress the aircraft within a reasonable amount of time. Flight attendant training, lighted pathways, pre-flight briefings, and fire-suppression systems are all examples of ways in which the egress process can be affected. The location of the accident and the preparedness of the local emergency response teams also play a large role in the ultimate survival of those passengers who survive the impact.

The objective of this program is to identify and prioritize the technologies or development efforts that will provide the largest effect for reducing fatalities in transport aircraft. A combination of case study and database analysis has been used.

2. BACKGROUND

2.1 ACCIDENT RATES

According to a 1998 National Transportation Safety Board (NTSB) report on accident rates, the number of hours flown, the number of departures, and the number of miles traveled by U.S. Air Carriers operating under 14 CFR 121 have all steadily increased from 1982 to 1998 (Reference 2). Hours flown by aircraft under CFR 121 increased from 7.04 million hours in 1982 to 16.51 million hours in 1998. The number of miles flown increased from 2.94 billion in 1982 to 6.77 billion miles in 1998. The total number of departures increased from 5.35 million in 1982 to 10.32 million departures in 1998. Although the total number of accidents has varied substantially by year, there has been a general increase over this time period due in part to the increased total number of accidents in the past 5 years.

However, the number of fatal accidents has not increased over this time period and has remained relatively constant over the years, averaging 3 fatal accidents out of an average of 25 total accidents per year. When comparing the number of total and fatal accidents per year with the total hours flown in that year, it is clear that the rate of total accidents per flight hour remained close to constant, while the rate of fatal accidents per flight hour slightly decreased over this time period, as shown in Figure 1. Since the number of accidents, hours flown, miles flown, and departures have all increased over this time period, it can be concluded that safety improvements have been occurring.

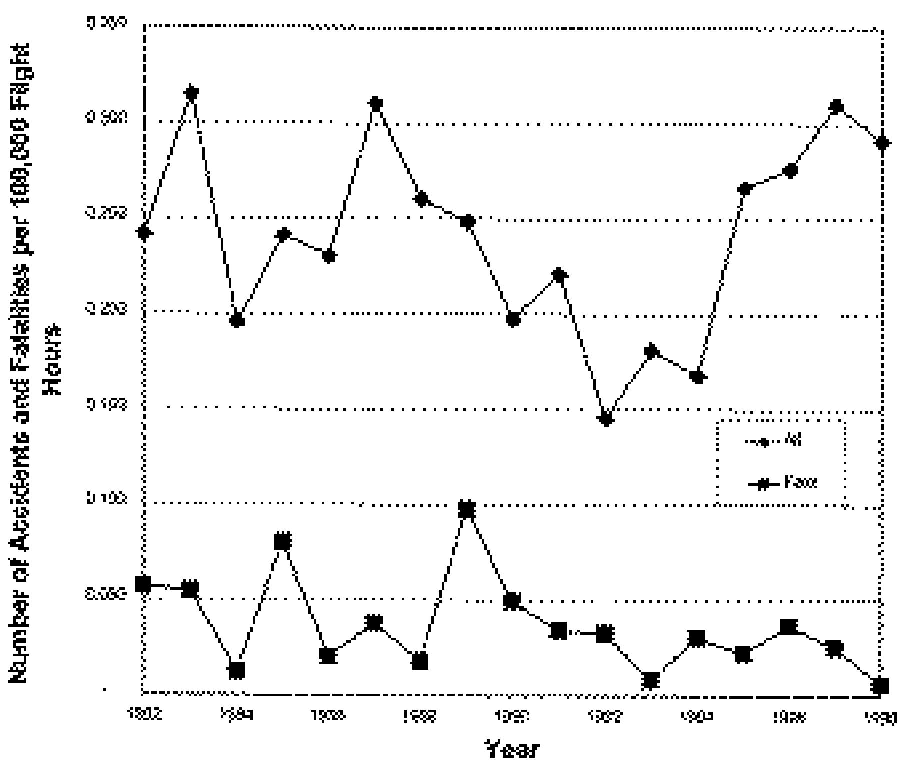

Figure 1.
Accidents and fatalities per 100,000 flight hours.

2.2 FATALITIES BY ACCIDENT CAUSES

According to a 1997 report by Boeing, the most fatalities and accidents in the worldwide commercial jet fleet between 1988 and 1997 were caused by controlled flight into terrain (CFIT). Of the 126 total accidents within this time period, 36 (28.6 pct) were due to CFIT, causing 2,806 fatalities. The second-highest fatality total occurred during accidents caused by in-flight loss of control, accounting for 31 accidents (24.6 pct) and 1,932 fatalities. While mid-air collisions and in-flight fire were the cause of only 2 accidents each, they accounted for a total of 506 and 371 fatalities, respectively, making them the next most hazardous accident causes (Reference 2).

2.3 ACCIDENTS BY PHASE OF FLIGHT

Accidents and fatalities occurring in the worldwide commercial jet fleet between 1988 and 1997 were categorized in a 1997 Boeing report (Reference 3). They found that the majority of accidents occur during the very beginning or the very end of the flight duration. A total of 47 pct of the accidents occurred at the end of the flights either during final approach (11 pct) or landing (36 pct), while 21 pct of the accidents occurred at the beginning of the flight, either during takeoff (16 pct) or during the initial climb (5 pct).

The number of fatalities per phase of flight was more evenly distributed. The most fatalities occurred during the end of the flight, with 30 pct occurring either during final approach or landing, followed by 23 pct during the climb, 17 pct during the initial approach, and approximately 10 pct for each phase of cruise, descent, or either take-off or initial climb.

2.4 PAST RECOMMENDATIONS TO IMPROVE TRANSPORT AIRCRAFT CRASH SAFETY

Previous studies of transport-category aircraft accidents have led researchers to make a number of recommendations to improve aircraft safety. Because of the prevalence of occupant injuries associated with proximal seat impact in transport aircraft, several investigators have suggested the implementation of shoulder harnesses to reduce the amount of occupant forward rotation that could lead to head and body strikes. One clear application of shoulder harnesses to prevent fatal injury was summed up in a report about the 1987 Continental Flight 1713 accident in Denver, Colorado (Reference 4). There were a total of 28 fatalities, of which only 6 received fatal blunt head injuries and another 8 received a combination of head and body injuries. The authors stated that it was unclear what effect a better restraint system could have had on passenger survival, but they concluded that, at a minimum, a three-point lap-and-shoulder harness system would have significantly improved survival in the six individuals succumbing to blunt head injury alone. They further proposed that minor alterations in aircraft design (secure bolting of the passenger seats to the airplane superstructure) and passenger restraint (a three-point lap-and-shoulder harness system) would positively influence the possibility of occupant survival during an airplane crash at negligible increased airline expense or passenger inconvenience.

In a similar analysis of injuries from a 1990 Cove Neck accident in which there were 73 fatalities out of 158 passengers, Dulchavsky reported the majority of passengers who died (64 pct) exhibited head injuries caused by cranial impact on the surrounding seats and aircraft structural elements (Reference 5). Since the crash occurred during final approach, it was assumed that all passengers were wearing their lap belt restraints and that the head injuries were primarily due to impact on the posterior portion of the adjoining seats. From patterns of injury to the head and upper torso of the restrained passengers in this crash, the authors suggested that a method of restraint incorporating a shoulder harness might decrease the incidence of fatal injury seen in these accidents.

There have been a number of accidents over the years involving serious injuries and fatalities attributed to seat-to-floor connection failures. As recently as the summer of 1999, investigators found that some passenger seats came out of their tracks on impact and scattered about the cabin in the American Airlines crash in Little Rock, Arkansas (Reference 6). This is why some aviation safety advocates have been pressing for sturdier airplane seats since 1970. In an early study of 27 survivable ground and 3 in-flight turbulence accidents between 1970 and 1978, Chandler, et al., concluded that seat performance continued to be a factor affecting safety in these crashes (Reference 7). They found failures ranging from seat pan collapse to the complete breakaway of the seat assembly from the floor, frequently attributable to floor and cabin deformation. They concluded that good seat performance under adverse conditions appeared to be attributable to a reduction of floor deformations or to the use of energy-absorption concepts.

In an early study on the kinematics of human motion during deceleration on transport aircraft published in 1962, Swearingen, et al., measured flailing curves of a seated passenger restrained only by a seat belt in a forward-facing seat and theorized that it was obvious that they would strike the seat directly ahead (Reference 8). He therefore concluded that since adequate spacing to prevent flailing strikes was impractical, efforts to increase crash survival must be aimed at: a) the delethalization of the seats to maintain impact forces below human tolerance levels and (b) improved seat anchorages to ensure that seats remain in place until the aircraft cabin itself disintegrates. This finding was later expanded upon in a 1988 paper by Desjardins, et al., on seat function in terms of crashworthiness (Reference 9). The authors felt that seats must: 1) carry the inertial loads of the occupant and seat and limit floor reaction loads to magnitudes not exceeding the floor strength, 2) minimize the hazard associated with secondary impact of the occupants with the seat in front, and 3) not leave the occupant in a position or orientation that significantly impedes egress.

One of the most prominent safety concerns in transport aircraft over the years has been in preventing deaths due to smoke inhalation and fire. There have been a number of accidents in which fires have broken out in the aircraft cabin while it was still on the ground and many occupants have needlessly died due to asphyxiation or burns because they were not able to egress the aircraft. In an article describing the safety of transport aircraft in 1984, Newsweek Magazine quoted the NTSB reports that indicated about 1 in 5 passengers killed in U.S. plane crashes died in a post-crash fire – 480 between 1965 and 1979 (Reference 10). While there have been advancements in making seat upholstery and the cabin interior more fire retardant, there are still numerous issues that must be addressed to ensure occupants are able to egress after a fire has started in the cabin. Safety aids such as smoke hoods and emergency lighting have been investigated throughout the years as egress-assisting devices. In the 1970's, scientists at the FAA’s Civil Aero-Medical Institute (CAMI) in Oklahoma City demonstrated that floor-level exit lights could prevent 20 percent of post-crash fatalities, so the NTSB began recommending the lighting for use in all transport aircraft from that time (Reference 10).

3. STUDY METHODOLOGY

This study utilized a combination of database reviews and case studies to determine and prioritize appropriate technologies for reducing fatalities in transport aircraft accidents. The NTSB on-line database was used for a quantitative review of accident scenarios, as well as to down-select accidents for detailed case-study review. The NTSB database was used to create a Simula Technologies in-house database from which further categorization of accident types was possible. The detailed case studies allowed consideration of which specific safety technologies would provide the most benefit in reducing fatalities and serious injuries. The database was used to identify the relative priority of the technologies based, in part, on the relative likelihood of the various accident scenarios.

3.1 DATABASE REVIEW

The on-line NTSB database provides an excellent source of accident overviews. Simula downloaded information from the on-line database to form the basis of an internal database built using Microsoft Access. The accident date, location, aircraft make/model, tail number, operator, and an abstract describing the accident were downloaded from the NTSB web site. Simula's search was limited to aircraft operating under CFR Parts 121 and 129. Data was available on-line for accidents starting at January 1, 1983. The most recent accident added to Simula's review was April 31, 1999. A total of 494 accidents, fatal and non-fatal, are catalogued in the database. The scenarios termed “incidents” by the NTSB were not included, as these accidents do not involve serious injury or fatality.

From the abstract provided for each accident, additional information regarding the accident was extracted (Figure 2). Additional information tallied included accident severity, accident survivability, the stage of flight in which the accident occurred, a categorical description of the accident, the number of people on board, the number of survivors, the number of fatalities, a categorical and textual description of injury cause, any incidence of post-crash fire, whether the final resting position of the aircraft was inverted, and whether the impacted surface was water. When information was not reported or when the data presented was insufficient, the category "unknown" was used or a negative response was assumed.

Accident data was filtered to remove accidents that were not relevant for this study or in which there was insufficient information for review. Accidents removed from the analysis included non-survivable accidents (defined as any accident in which there were no survivors [e.g. TWA Flight 800]) accidents in which there were no injuries, accidents involving ground crew only, accidents in which no aircraft was recovered, and accidents for which no abstract was available.

Using the above selection criteria, 209 accidents remained for study. The accidents were further classified as survivable or partially survivable. A survivable accident was defined as an accident in which there were no fatalities. A partially survivable accident was defined as an accident in which there was at least one fatality and one survivor among the people on board the aircraft. Because of a lack of detailed information in the abstracts, no attempt was made to distinguish accident survivability based on aircraft structure or crash conditions. Within the study sample, there were 183 accidents considered survivable and 26 accidents considered partially survivable. As a final sort, the 103 survivable or partially survivable accidents in which turbulence was the only cause of injury were removed from the sample.

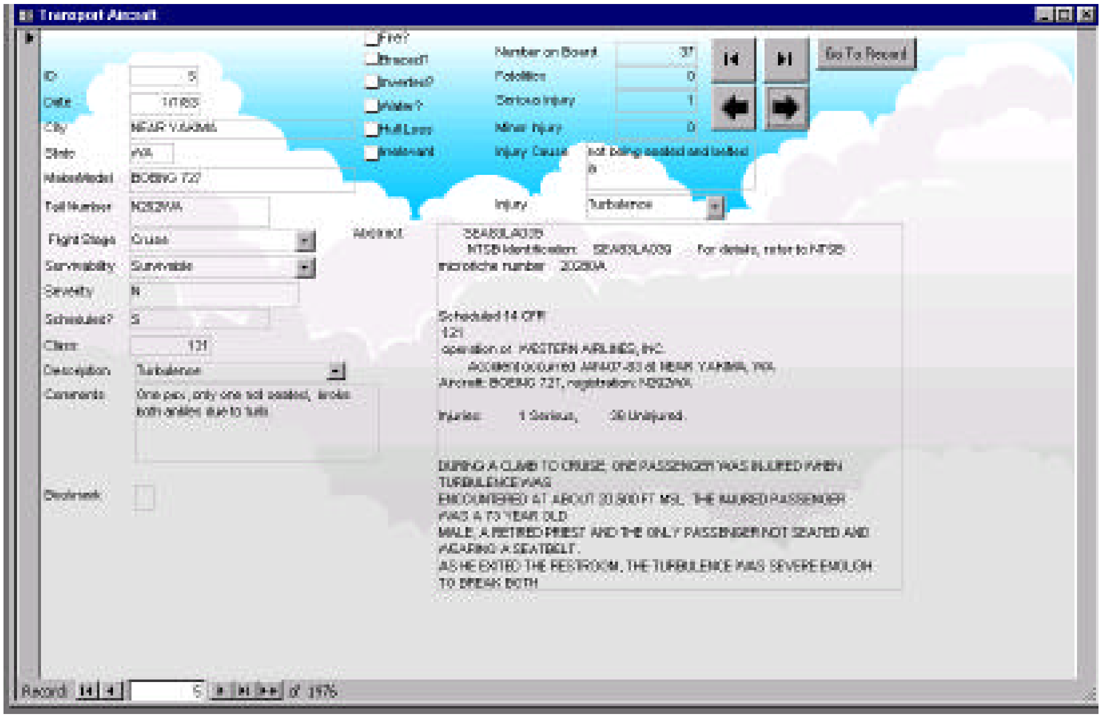

Figure 2.
Data collection form.

3.2 CASE STUDIES

Eleven transport-category aircraft accidents that occurred between 1985 and 1994 were reviewed in detail using NTSB official reports and information from people who were on-scene at the accidents or participated in the accident investigation (Table 1). All accidents selected for full case study were those deemed to be partially survivable, as defined above as an accident in which there was at least one survivor and one fatality on board the aircraft.

The following summarizes the selection criteria that were used to determine the accidents for review:

- One or more fatality on board the aircraft, one or more survivor aboard the aircraft
- Accident date: 1983 - 1994
- Sufficient data available for evaluation (NTSB or AAIB). Accident investigation completed.
- Diversity of accident scenarios (e.g., water impact, post-crash fire)
- U.S.-based airline and accident on U.S. preferred

The selected accidents range in severity from a 1989 accident in New York that produced two fatalities in an otherwise survivable event to a 1987 Detroit accident in which only one occupant survived. The scenarios range from an in-flight emergency which led to a crash in a cornfield in Iowa to an accident in which 15 people survived the impact but drowned in cold water while attempting to egress the aircraft. Case studies were performed of almost every partially survivable accident in the U.S. in this time period. The level of detail of the case report was the limiting factor in the level of detail in the investigation. For the most part, Simula was limited to

Table 1.
Transport-category aircraft accidents selected for review

Year	Location	Operator and Aircraft	Cause of Accident	No. of Fatalities/ No. of Survivors
1989	Sioux City, IA	United DC-10-	Engine Failure	111/172
1988	Dallas/Ft. Worth, TX	Delta 727-232	Operational	14/76
1989	Kegworth, England	British Midland 737-400	Engine Failure, Operational	47/79
1991	Los Angeles, CA	Boeing 737 and Fairchild Metroliner	On-ground collision	22/69 on B737, 12/0 on Fairchild
1992	Flushing, NY	USAir Fokker 28-4000	Icing / Take-off	27/24
1985	Dallas/Ft. Worth, TX	Delta L1011-385-1	Weather	135/28
1987	Romulus, MI	Northwest MD-DC-9-82	Operational / Take-off	155/1 (1/5 on ground)
1987	Denver, CO	Continental MD-DC-9-14	Icing / Take-off	28/54
1994	Charlotte, NC	USAir MD-DC-9-14	Weather	37/20
1989	Flushing, NY	USAir Boeing 737-400	Operational / Take-off	2/21
1990	Cove Neck, NY	Avianca Boeing 707-321B	Landing, Fuel Exhaustion	73/85

the data presented in the publicly available NTSB final reports. For the older accidents, good, detailed photographs were not included in the NTSB reports. Autopsy reports were also not included for many of the accidents.

A team was gathered to review the case studies. The team consisted of Dr. Dennis Shanahan (ARCCA), Mr. Richard Chandler (C, Inc.), Mr. Darrel Noland (Simula), and Ms. Anita Grierson (Simula). Dr. Shanahan and Mr. Chandler have participated in numerous aircraft investigations. Mr. Noland is experienced in small aircraft interior design and certification. Ms. Grierson is a Biomechanical Engineer with experience in aircraft seat design and certification.
Ms. Lisa Jones (NASA) also participated in some of the accident reviews.

For each detailed case study, mechanisms of injury and methods and complications for egress and post-crash survival were determined. Situations for fatalities, survivors, and uninjured passengers were compared. From this analysis, the needs of the occupants that went unmet by the available technologies were determined. Since aircraft accidents are very complex events, and because detailed occupant reconstructions were beyond the scope of the study, it was not possible to say with certainty if a specific safety technology would have been able to prevent the fatality or serious injury for a specific individual. The outcome of the case studies was a list of potential safety technologies, with some details on the design or performance requirements for each technology.

3.3 TECHNOLOGY PRIORITIZATION

The case studies were used to determine which safety technologies would have been of potential benefit in reducing fatalities in partially survivable accidents. The database results were used to determine the relative frequency of these scenarios. While each accident is unique, there are some similar factors that can be used to make an assessment of relative benefit provided by each technology. These numbers provide a rational basis by which the technologies can be prioritized for review and potential implementation.

4. DATABASE RESULTS

Simula Technologies' initial database included 494 Part 121 and 129 accidents. Of those 494 accidents, 54 were categorized as non-survivable, 32 as partially survivable, 390 as survivable, and 18 as unknown. These records were further down-selected based on relevance to the review and whether there was sufficient information available for preliminary review. The non-survivable accidents were also removed at this time.

A database of 209 survivable and partially survivable accidents from 1983 to 1999 remained, from which quantitative comparisons of the accident scenarios were developed. The review was broken down into the cause of the accident, the phase of flight during which the accident occurred, injury causes, and additional accident descriptors (e.g., fire, aircraft inversion, water impact).

During the initial analysis, it was determined that turbulence was by far the most common cause of those events categorized as accidents. Turbulence accounted for 49 pct of all accidents and 54 pct of the accidents in which no fatalities occurred. In order to evaluate causes of injury related to crash events, the accidents related to turbulence were removed from the analysis and are discussed separately. A total of 106 accidents remained for analysis. Of these 106 accidents, 25 were partially survivable (at least one fatality and one survivor) and 81 were survivable (no fatalities).

The cause of the accident was defined as the scenario that led to the production of injury. No attempt was made to distinguish cause in standard terms such as mechanical or human error. Figure 3 shows the accident cause for the 106 accidents reviewed. For partially survivable accidents, the most frequent type of accident was an in-flight emergency, followed by on-ground collisions. Emergency evacuations dominated the accident cause where survivable accidents are concerned. The “other” category was composed of scenarios such as mechanical failure of jet ways and handrails, taxiing accidents, and various relatively unique events.

The next feature examined was the phase of flight that the aircraft was in when the accident sequence was initiated. Figure 4 demonstrates the phase of flight for the study sample. As expected, in partially survivable accidents, the phase of flight is dominated by the take-off and landing phases (78 pct were landing, approach, take-off, or climb-out accidents). Survivable accidents are dominated by static accidents, which is consistent with the large number of emergency evacuations.

From the abstracts presented in the NTSB database, it was difficult to ascertain the cause of the accident unless it was specifically stated, which occurred only for a few of the accidents. However, based on the information presented, assumptions could be made as to the cause of injury, particularly focusing on separating those accidents predominated by evacuation injuries, blunt force trauma, and fire exposure or smoke inhalation. Only one injury classification was used for each accident, although it is clear that several types of injury mechanisms are present in complex accident scenarios.

Figure 5 shows the breakdown of injury types based on accident severity. Blunt force trauma clearly dominates as the cause of injury in partially survivable accidents. Fire and smoke inhalation only accounted for 8 pct of partially survivable accident injuries. Evacuation and egress injuries predominate as the cause of injury for survivable accidents.

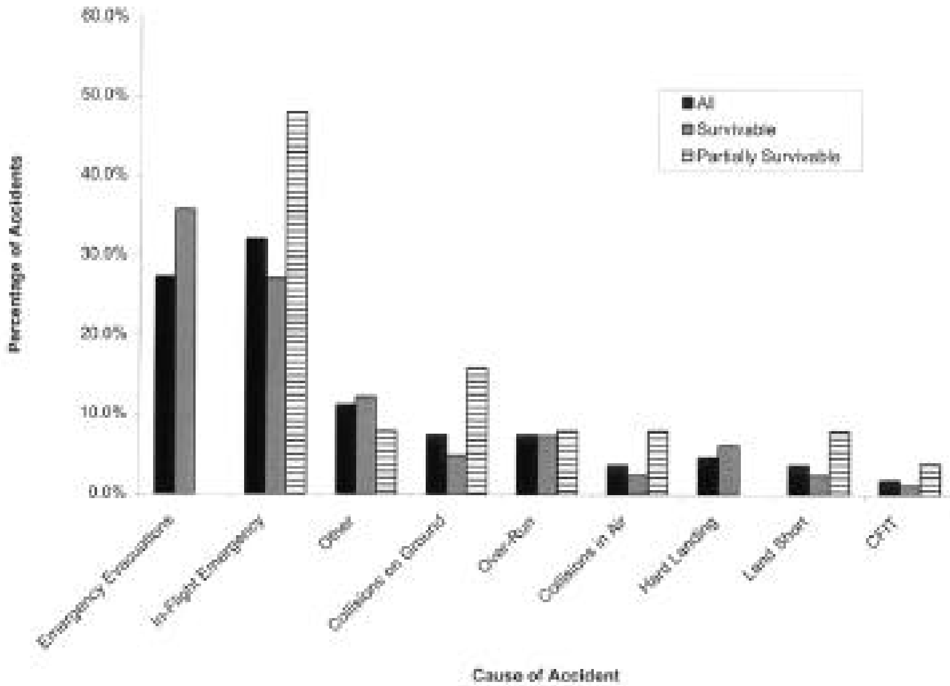

Figure 3.
Cause of the accident.

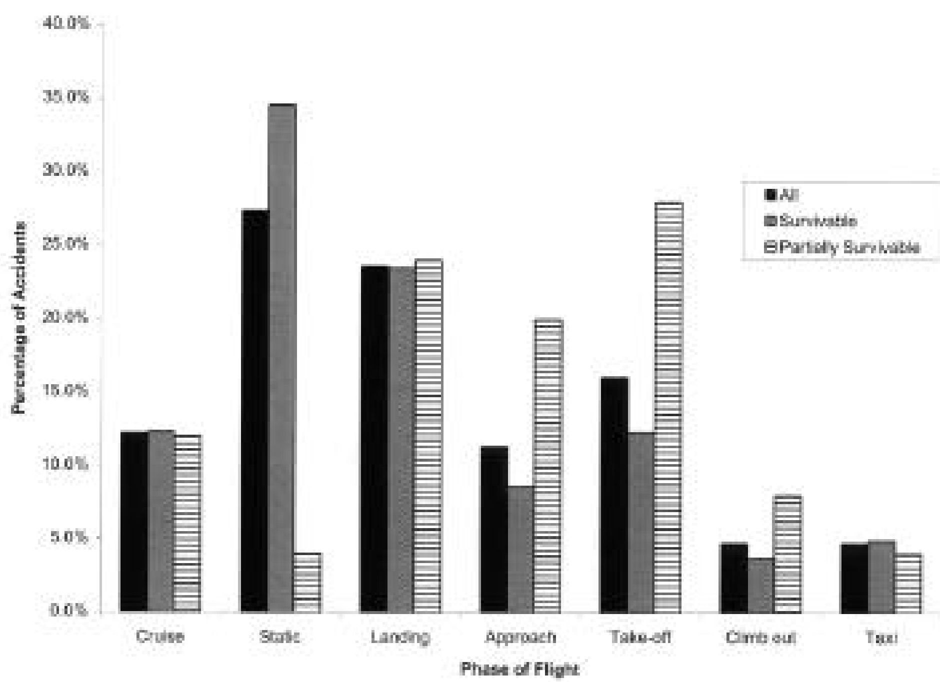

Figure 4.
Phase of flight in which the event was initiated.

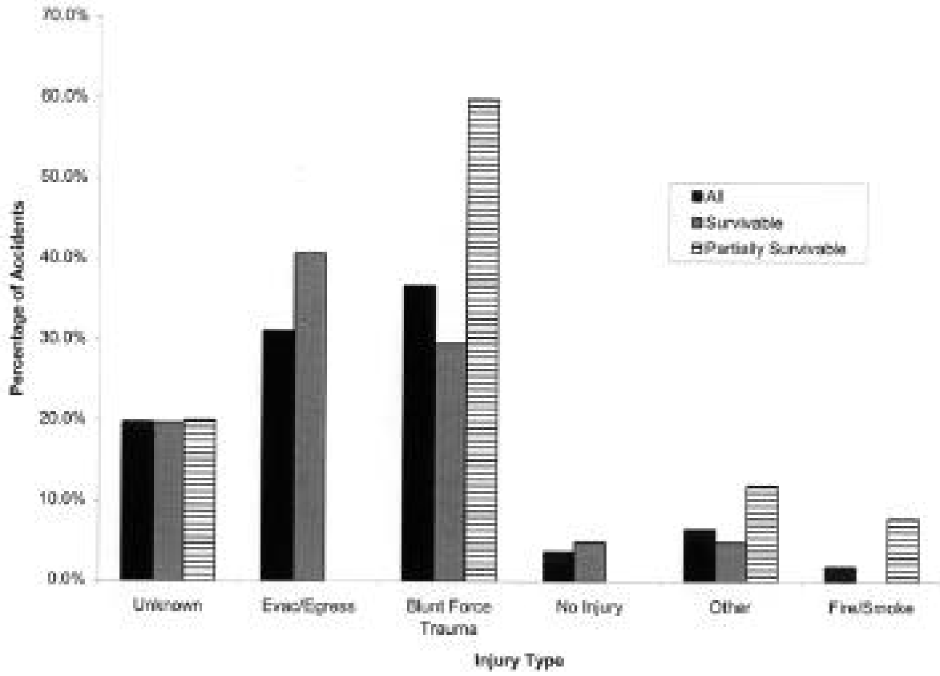

Figure 5.
Injury type in each accident.

The next step in evaluating injury was to review the severity of injury. The NTSB classified injuries as fatal, serious, or minor. Of the 106 accidents, 21.7 pct (23 accidents) included fatalities. A total of 13,487 people were on board the aircraft during the 106 accidents. Of these, 1,219 (9.0 pct) suffered fatal injuries, 469 (3.5 pct) suffered serious injuries and 1,048 (7.8 pct) suffered minor injuries. Using the same categories as above – cause of accident, phase of flight, and injury type – the injury severity is broken down further.

Examining the variation in injury severity with the cause of the accident (Figure 6) clearly demonstrates that mid-air collisions, CFIT, and landing short of the runway produce a high level of fatalities. Of these three, the leading cause of fatal accidents is CFIT. The severity of this accident mechanism is not clearly demonstrated by this study, since many of the CFIT accidents are without survivors.

Injury severity in relation to the phase of flight in which the accident sequence was initiated is shown in Figure 7. The approach, climb-out, and landing phases all show a substantial rate of fatality. As expected, static accidents, taxi accidents, and those which happen during the cruise phase are often limited in the severity of injuries produced.

Injury severity related to the type of injury is examined in Figure 8. The results are as would be expected, with fire and smoke inhalation producing fatalities at the highest rate, while emergency evacuations are relatively benign events.

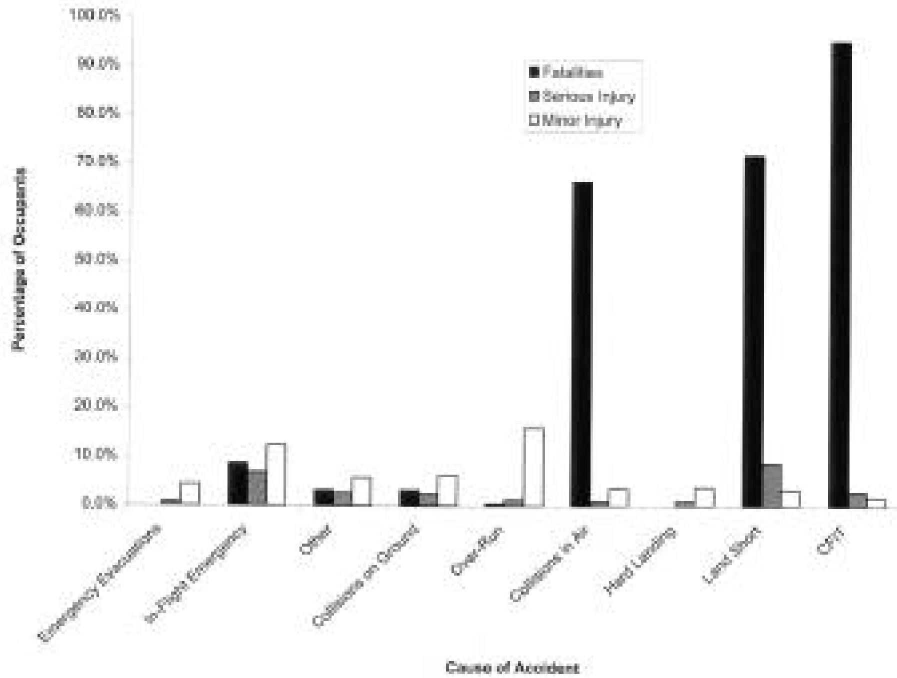

Figure 6.
Injury severity and cause of accident.

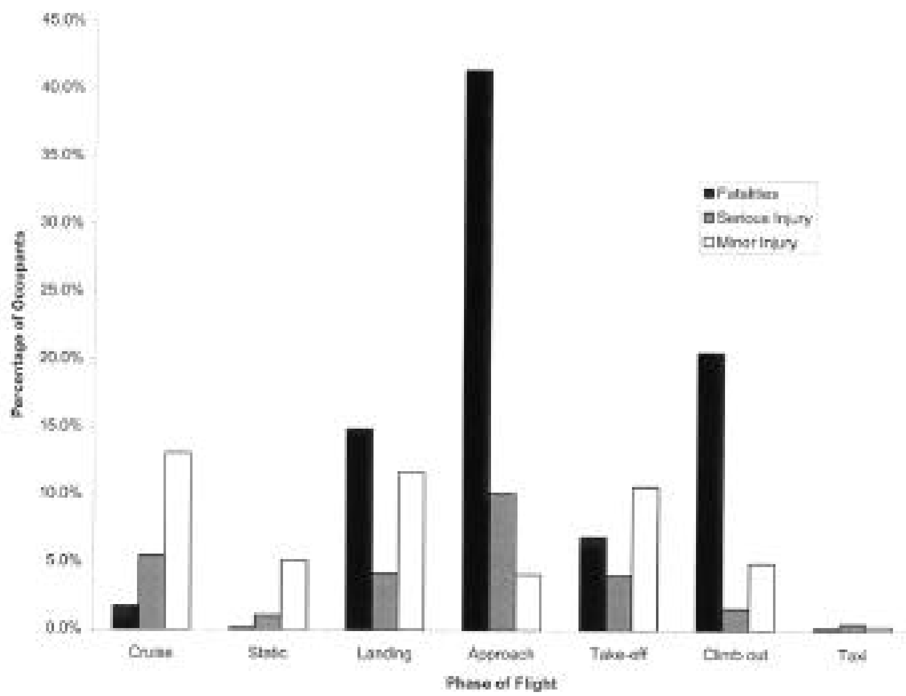

Figure 7.
Injury severity and phase of flight.

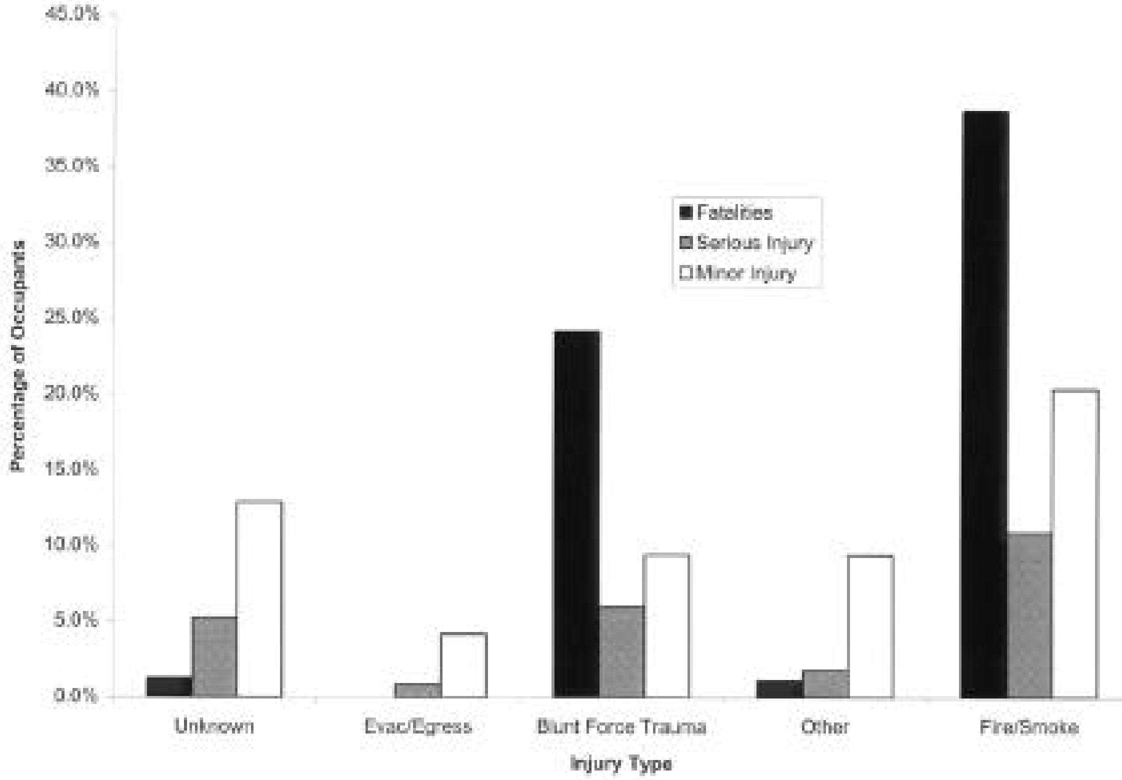

Figure 8.
Injury severity and injury type.

Turbulence accounted for 103 of the accidents in the database. In order for a turbulence event to be categorized in the database it had to be considered an “accident” instead of an “incident” by the NTSB. Accidents are only categorized if there was a serious injury to a person or to the aircraft. There were 457 minor injuries, 139 serious injuries, and 1 fatality attributed to turbulence accidents. Of these accidents, 52 pct happened to a crewmember, 40 pct to a passenger, and 8 pct were unknown. An average of 5.8 people were injured per event, although many accidents had only 1 injury, and 1 accident alone resulted in 40 injured occupants. Most of the listed injuries were to the legs and ankles, but other body segments injured included the back, shoulder, lumbar spine, and head. The majority of injuries occurred while the aircraft was in the cruise phase of flight (85.4 pct).

While fires, water impacts, and inversion of the aircraft do not happen frequently, they complicate post-crash survival considerably. Using the database, a search was conducted for these factors. The occurrence of each factor was likely to have been underestimated, since the accidents were not recorded as having that factor unless it was specifically mentioned in the abstract.

Of the accidents in the database, 11 accidents were complicated by fire. In three of the accidents in the database, the aircraft ended up in water. Of the 291 occupants on these three flights, 29 (10 pct) were fatalities, 27 of which were in one accident. The other two fatalities were due to hull loss, with the water having little impact on occupant survivability. Serious and minor injuries accounted for 4 pct and 14 pct of all injuries, respectively, and 71 pct of the 291 people suffered no injuries. It is important to note that the NTSB listed pilot error as the cause of these three accidents. As pilot error cannot be eliminated, it may be assumed that these accident scenarios could be repeated.

In the case study review, the inversion of an aircraft or a section of aircraft was a complicating factor for passenger egress, often leading passengers to suffer injury as they extricated themselves from their seats. Only two accidents were identified in the database review that involved an aircraft being inverted during passenger egress. Both of these were partially survivable and were covered in the detailed case studies.

5. CASE STUDY RESULTS AND ANALYSIS

A total of 11 transport-category accidents were selected for review. The 11 accidents were reviewed to various levels of detail, depending upon the information available for analysis. While reviewing each accident, Simula Technologies worked with a team of experts to determine the basic accident kinematics, the types of injuries received, the mechanisms for injury, and the distribution of injuries within the aircraft. From this data, the group was able to draw conclusions about injury causation, identify which technologies would help to prevent injury, and determine which technologies, had they been available, would have made a difference in reducing the rate of fatality and injury.

Since the purpose of this study is to identify means to reduce injury and fatality in potentially survivable aviation accidents, the results of the case studies are reported in relation to the factors that affect occupant survivability. After looking at the specific findings from the case reviews, and considering that no two accidents are exactly alike, judgement must be used in expanding those results to other potential scenarios. The following section is organized around the factors required for occupant survival, followed by discussions of some of the special circumstances, such as child passenger protection and turbulence protection, that will also lead to decreased incidence of serious injury and fatality.

5.1 MAINTAINING OCCUPIABLE SPACE

To survive an accident, a livable volume of space around the occupant must be maintained. When aircraft structure deforms into passenger spaces, lessening the occupiable volume, chances for survival are severely compromised. Livable volume can be lost through general crushing of aircraft structure due to longitudinal and vertical impact loading, through localized loading of the aircraft, and through break-up of the aircraft as the fuselage impacts the ground. Localized loading from impacts with structures, ground features, or other aircraft can lead to localized hull breach and loss of life in accidents that are survivable in all other respects. Since aircraft are designed primarily to fly, and seldom crash, it is understandable that they are not designed with the same reinforced passenger compartments as are found in race cars or even in many standard automobiles. However, the way in which an aircraft is structurally designed, and its ability to maintain a survivable occupant volume, will affect occupant survivability.

A partially survivable accident usually occurs with substantial accompanying damage to the aircraft structure – either induced by localized loading of the aircraft through contact with external structures, or by impact forces overstressing the aircraft fuselage. The severity of occupant injury and the overall level of survivability, are often directly correlated to the degree of structural damage. In other words, in partially survivable accidents, survivors are often differentiated from non-survivors because of the amount of damage to the area of the fuselage in which they were sitting. The areas of the aircraft that have the highest levels of survivors are those areas that remain largely intact. The areas that remain intact vary from accident to accident, particularly in cases where aircraft invert. For example, the overwing area is often considered the safest for passengers due to the reinforced structure over the wing box. However, in the 1987 Denver accident, fatalities were high over the wing box, partially due to loss of occupiable space in that area when that aircraft section inverted.

To a certain extent, the locations at which an aircraft will break can be predicted. The most likely locations for fuselage break-up are those in which there are discontinuities in aircraft stiffness; specifically, behind the nose of the aircraft, immediately before and aft of the wingbox, and forward of the tail section. The 1989 Sioux City and the 1989 Kegworth accidents resulted in each aircraft breaking into multiple sections near these locations (Figures 9 and 10).

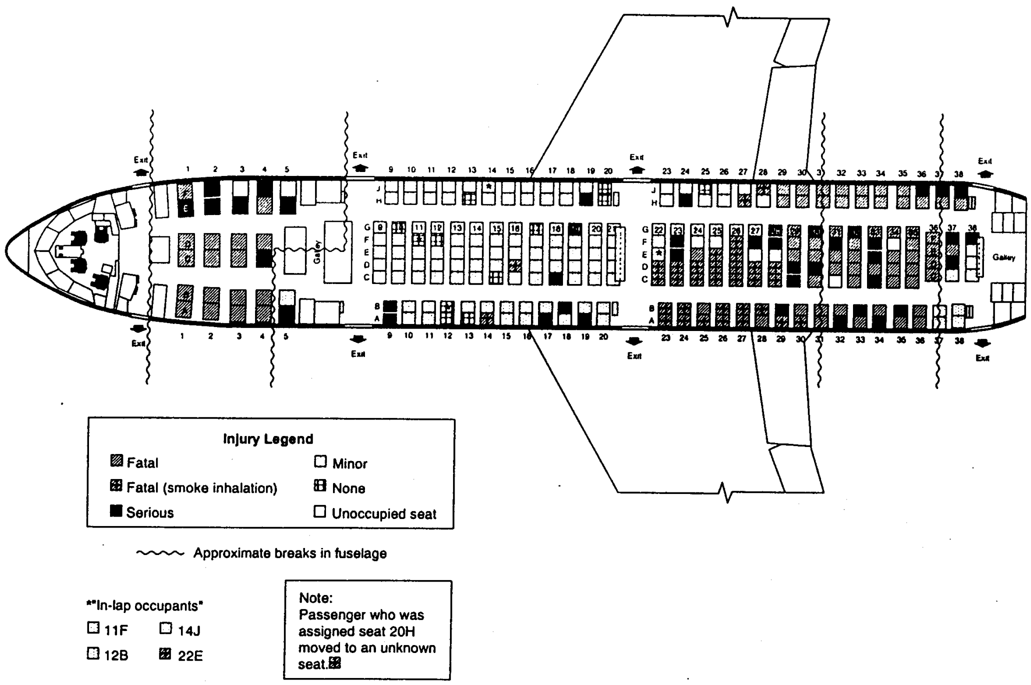

Figure 9.
Fuselage damage and aircraft interior layout from the 1989 Sioux City accident.

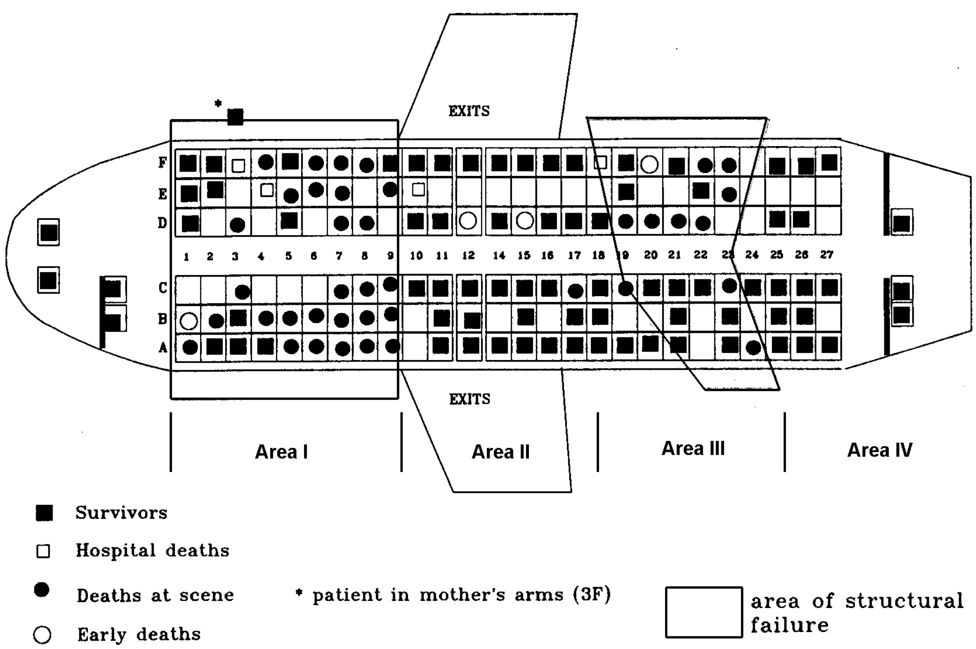

Figure 10.
Fuselage damage and aircraft interior layout from the 1989 Kegworth accident.

In a detailed study of the 1989 Kegworth accident, White, et al., correlated the structural damage to the severity of injury (Reference 11). Structural damage to the aircraft fuselage, floor, and interior structure was greatest near the large breaks in aircraft structure. Their work showed a positive correlation between structural damage of the interior and the seating system and the severity of injury as measured through an Injury Severity Score (ISS) (Figure 11). The highest interior damage scores were in the areas of fuselage disruption. Fatalities predominantly occurred in the section of aircraft forward of the wingbox, and in the area between the wingbox and the tail section.

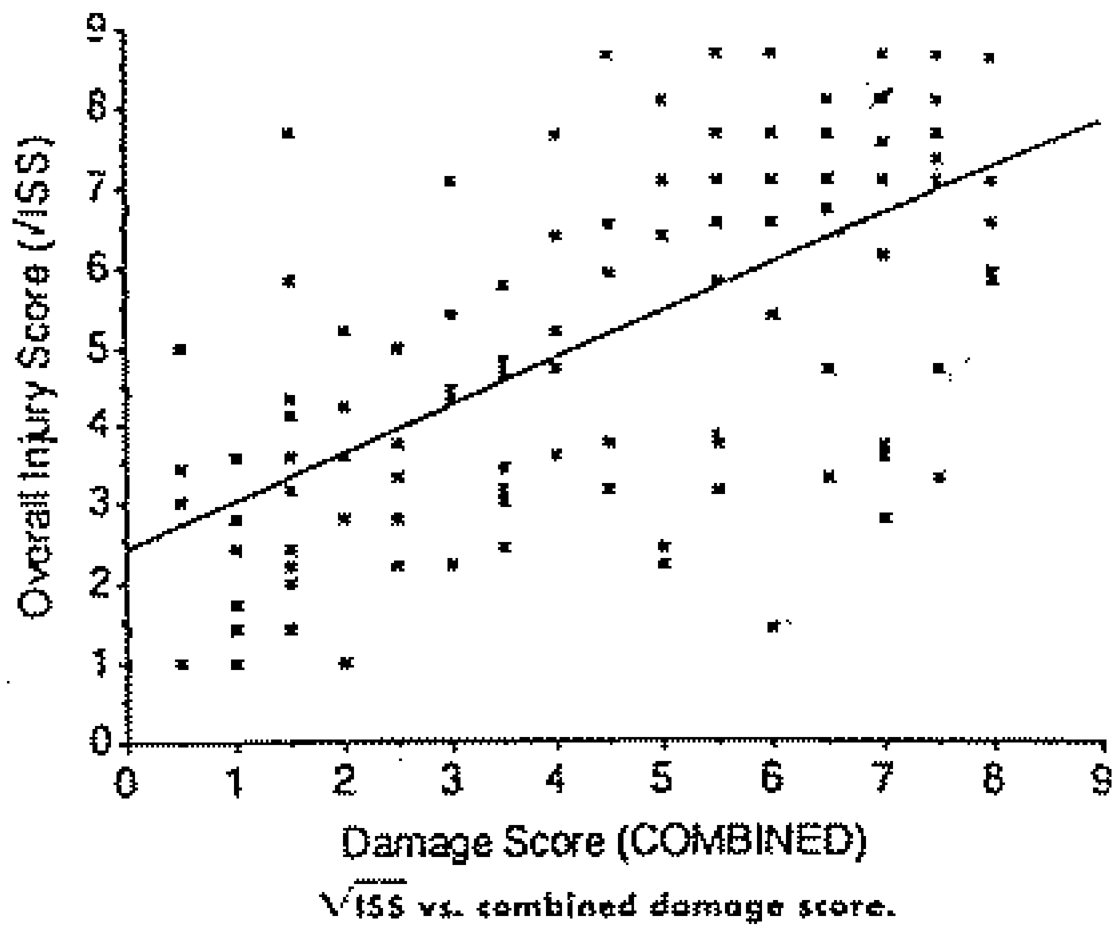

Figure 11.
Positive correlation between aircraft and seat damage and Injury Severity Score in the 1989 Kegworth accident (Reference 11).

Localized loading can also lead to serious injury and fatality. In a 1989 accident in Flushing, New York, two fatalities and three serious injuries occurred when an aircraft ran off the end of the runway and into a body of water following a rejected take-off. The Boeing 737-400 aircraft separated between Rows 3 and 5 and between Rows 19 and 21. Structural damage to the interior compartment was most severe near the rear break, where damage was mostly due to contact with a reinforced concrete pillar. In this rear section, the floor buckled upwards, crushing two passengers and entrapping two others. The fatalities occurred due to mechanical asphyxia, essentially a crushing of the chest by intruding structures. Two of the serious injuries occurred to passengers who were trapped in their seats, also in the area of the rear break. These passengers were not able to extricate themselves from their seats. Passengers able to egress the aircraft were not able to move past this section of the aircraft. Had there been a fire or had the aircraft been in deeper water, the trapped occupants might not have survived, as they were not rescued until 45 and 90 minutes after the accident. Elsewhere in the aircraft, the level of structural deformation and the impact loading was sufficiently low to allow passengers to survive the impact, and then to egress under their own power. The third serious injury was incurred during rescue operations. The only other injuries were minor “flail type” injuries such as hand and foot fractures or abrasions, or mild cervical sprain from hitting the seat in front. Seat damage was also most serious in the area near the rear fuselage break, with only minor damage in other areas. With the exception of the immediate area of the aircraft damage, this accident was completely survivable.

Structural damage to the aircraft, through crushing or through the aircraft breaking up on impact, can lead to a decrease in the area around the occupant. In other modes of transportation, the method for maintaining an occupiable volume around occupants is to increase the crash-worthiness of the structure surrounding the occupants. Examples of this include reinforced structures around racing car cockpits and the use of rollbars. However, this solution is not likely to be viable for aircraft fuselage design. Weight penalties are high for aircraft, so the benefits provided by reinforced structures may not prove sufficient to overcome the substantial cost, particularly in retrofit applications.

A long-term solution to improving occupant survivability is to design the aircraft fuselage so that break points are designed into the structure. The fuselage could be designed to separate at specific locations and in a way that reduces the hazards that presently occur at the locations of the split. This type of technology would have to be incorporated in future aircraft designs and would likely affect the design of many sub-systems on the aircraft, such as fuel and electrical systems. New materials and structural designs may provide solutions that do not substantially increase the aircraft's weight.

Of the 11 case studies performed, survivability would have been increased in 8 of the 11 cases if the aircraft break locations or crush zones could have been delethalized. A shorter-term solution could be to remove rows of seats in areas that are known to be most likely for structural damage. While the airlines will not find it desirable to remove revenue-producing seats, it is conceivable that the interior could be re-designed to place lavatories, galleys, bulkheads, carry-on baggage storage, or other non-passenger items in these areas. Limiting the number of people who occupy the critical break-up areas of the aircraft will reduce the number of fatalities in serious but survivable crashes.

Paradoxically, in some cases, aircraft break-up is beneficial. The holes created in the aircraft structure may provide the only means for occupant egress when exit doors cannot be opened due to damage or external hazards. Typically, when an aircraft's fuselage crushes or breaks apart, sharp edges are created from the torn metal and a maze of wires, cables, insulation, and other aircraft system parts are left in the opening. When the aircraft is severely damaged, breaks in the aircraft structure may provide the only routes of escape for passengers. For example, the 1994 crash of a DC-9 near Charlotte, North Carolina, when one of the emergency exits was blocked by fire, a group of people exited through a small hole near the tail of the aircraft. According to the flight attendant's statement:

> "She assessed the tailcone exit door and determined that it would not be dangerous to open it. … They got the door open slightly and Ms. Forcht saw smoke and determined that the exit was not useable. " She next attempted to go to the window exits. "The aisle was blocked in front of her and the cabin was filled with heavy smoke and fumes. … She looked for an opening on aircraft left and found a small hole where she saw light below the passenger seats. She exited down and to the left through the hole as did an adult male, an adult female, and a small child."

An added benefit of controlled breakage of the fuselage would be in assisting egress in severe accidents when exit doors are not useable or when occupants must egress very rapidly (e.g., when there is fire or if the aircraft is in deep water).

5.2 TIE-DOWN CHAIN

If livable volume is maintained, the next requirement for improving survivability is to restrain the occupant within that volume. Specifically, the tie-down chain from the occupant to the aircraft structure must be maintained. This tie-down chain includes links between the fuselage, floor, seat track, seat, seat belt, and occupant. Compromising the tie-down chain at any of these links will lead to a lack of occupant restraint and subsequent injury or fatality. In the accidents reviewed, the tie-down chain usually failed either at the floor, from disruptions in the floor structure, or at the connection of the seat to the floor, with the seat ripping out of the floor structure. While the seat lap belts largely performed as designed in their ability to restrain the occupant to the seat, improvements to the design of the seat belt system would increase survivability.

5.2.1 16-G Seats

The 1989 accident in Kegworth, England, provides a clear demonstration of the ways in which the tie-down chain can be broken and the subsequent effects upon occupant survivability. This accident is of particular relevance because the seats on the aircraft were designed and tested to meet the structural portions of the 16-G dynamic test standards, i.e., FAR 25.562, Amendment No. 25-64 (Reference 12). All aircraft issued new type certificates after May 17,1988, are required to meet this standard. The remainder of the aircraft in this study had seats that were certified under a 9-G static test condition. The predominant reason for the 16-G standard was to improve the integrity of the link between the seat and the floor track during a severe but survivable impact scenario. Consequently, these new seats should have been able to stay in the floor tracks much better than previous seat designs.

Figure 12 shows the accident scenario for the 1989 Kegworth accident. For analysis of structural damage, the Boeing 737 aircraft was divided into four areas based on the breaks in the aircraft's structure (See Figure 9). Area I represented the passenger compartment from Row 1 to Row 9. Structural damage was worst in Rows 6-9 as the aircraft broke apart in this area. Area II was over the wing box. The aircraft structure remained relatively intact in this area. Area III was from the rear of the wing box to a break in the aircraft forward of the tail section. The right side of the aircraft in this area suffered severe structural damage. The aircraft hit the embankment at a slight yaw angle, which led to excessive crushing of the right side of the aircraft in this area. Area IV was the tail area of the aircraft that remained intact. As mentioned previously, survivability in this accident could be directly correlated with the degree of structural damage.

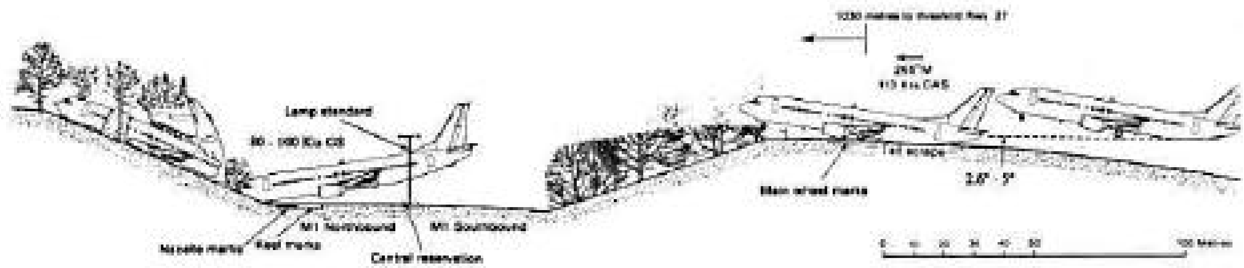

Figure 12.
Sketch of the accident scenario of the 1989 Kegworth Accident (Reference 13).

Area I showed the most structural damage. This section was crushed and floor integrity was lost. All of the floor beams failed in this area. Failure of the floor beams caused all of the seats to become loose and literally pile up on top of each other. Recovered seat backs from this area showed damage, presumably from contact with the person in the row behind the seat. Some seat failures were in evidence, but investigators speculated that the seat failure was preceded by the floor failure. Each passenger seat had U-shaped steel straps at the front leg track attachments that were designed to deform at the 16-G level. Of the 35 identified U straps, only 4 were un-deformed, indicating that loading in this area was likely greater than 16 G, and was probably closer to 20 G. Those U straps that remained un-deformed or only partially deformed were likely a result of un-symmetric loading of the seat structures. The majority of occupants in this section, particularly those near the rear break in the section, were fatally injured. Injuries in this section were mostly multiple extreme blunt trauma injuries. Given the failure of the aircraft structure, it is unlikely that any changes to the seating systems, overhead bins, or other interior items could have provided a significant reduction in fatalities. The aircraft structure in other sections of the aircraft did remain intact with concurrent improvement in occupant survivability. It is clear that an increase in the crashworthiness of the floor structure is the only technology that would have made a significant difference in survivability for those in this section of the aircraft.

In Area II, over the aircraft wings, the floor was reinforced with intercostal members. The floor showed evidence of high decelerative loading, but did not experience the massive failure as in Area I. The seats had varying levels of damage, consistent with forward and downward loading; however, all but two of the seats remained attached to the seat track and floor. Two seats of the seats that completely failed had bending failures of the front spar of the seat. Deformation of the front spar also occurred in other seats in this section. The U straps on the seats showed extensive damage, with 74 pct of the U straps fully collapsed, as compared to 37 pct fully collapsed in Area I. The loads transferred to the seats in this section were at least as high as those in Area I, but since the floor structure and the seats remained relatively intact, survivability was high. There were only four fatalities in this area, two of which White, et al., attributed to posterior head impact from an overhead luggage bin (Reference 11). Injuries in this area included a significant number of lower extremity and pelvic injuries. The type of lower extremity injury suffered likely depended upon the initial position of the lower extremity and upon the failure or deformation of the seat. Foot and ankle injuries were prevalent when the feet became entrapped in deforming or failing seats. Knee and pelvic injuries likely resulted when passengers slid forward in their seats to contact the seat in front of them. Virtually all passengers had pelvic bruising from the lap belts, with five iliac fractures attributed to seat belt loading. Several comminuted tibia/fibula fractures were also present. The reinforcement in floor structure, as compared to Area I, clearly contributed to increased survivability in this section. However, that in itself was not sufficient to prevent serious injuries, but merely shifted injury to potentially less fatal mechanisms. Seat deformation and the lack of sufficient occupant restraint within the seat also contributed to serious injury.

In Area III, the aircraft floor was also disrupted, but to a lesser extent than in Area I. Damage came as a result of both aircraft break-up aft of the wingbox and the crushing of the right side of the aircraft. Seat attachment integrity and seat damage corresponded positively with floor and structural damage, as did the level of occupant survivability. Many of the occupants in this area of the aircraft required extrication as they were trapped in their seats. The U straps on the seats were deformed, although to a lesser extent than in Areas I and II, indicating lower seat loading. Of the seats in this section that were severely damaged, all but one had detached seat backs, indicating that the seats suffered severe loading from behind as the occupants in those seats were thrown forward when their seats were released. The fatalities in this section were similar in nature to those in Area I, with crushing injuries predominating in the area of aircraft crush. Where there was less aircraft structural damage and subsequent floor and seat damage, the injuries were similar to those in Area II.

Area IV, the tail section, broke loose, jack-knifed, and ended up partially inverted. There was less structural damage in this section. Some seats were separated from the floor track; however, only one of the U-straps was deformed. The tail section experienced a less severe scenario than did the more forward sections. This is not surprising, since the aircraft impacted on an upward slope with the crushing of forward sections absorbing some of the impact energy. Correspondingly, there were no fatalities in this section and the overall level of injury in this section was the least severe.

By comparing the areas of damage and injuries incurred throughout the aircraft, it can clearly be seen that the retention of floor integrity was a critical factor in increased occupant survivability. Where the floor remained intact, the 16-G seats appear to have been stressed to the limits of their capabilities, as evidenced by the failure of some seats and by the deformation of the U straps. However, for the most part, the seats maintained their connection to the floor, which is a significant improvement over the performance of the 9-G statically tested seats.

To increase survivability, the requirements for floor crashworthiness must be increased. Without an increase in the structural integrity of the floor, the improvements in occupant protection afforded by improved seating systems and other interior safety upgrades will not reach their potential. The Air Accidents Investigation Board recommended an increase in floor structural integrity following the 1989 Kegworth crash (Reference 13). Specifically, a dynamic design standard that relates to human tolerance levels, or at least the seat dynamic standard, should be required. Additionally, it is important to seek to improve tolerance to out-of-plane loading, and to provide for multiple load paths. It is conceivable that floor strength could also be increased non-uniformly to meet the needs of the different aircraft sections. Increasing the crashworthiness of the floor structure must be a long-term consideration for improved survivability in aircraft accidents.

If the floor and the seats remain reasonably intact, as in Area II, the challenge then becomes improved restraint of the occupant within the seat. The current two-point restraints allow an occupant to slide forward along the seat pan several inches before the forward motion of the pelvis is stopped. While sliding forward, the occupant develops a relative velocity in relation to the seat, which increases the loading on the occupant when the seat belt finally acts to restrain the individual. The two-point lap belt also provides no restraint for the occupant's head and upper torso. Unless the occupant is in a braced position, the occupant's upper body is free to flail about during the impact. Increasing the restraint of the occupant's pelvis and providing some restraint for the upper torso are two mechanisms by which restraint can be improved. The technologies required are widely available. There are several potential technologies that could address this situation:

- Powered haul-back or inertia reels that limit forward excursion of the pelvis by eliminating slack in the restraint system
- Three-point restraints which limit torso flail, thereby limiting forward motion of the head, chest, and pelvis
- Alternative seat designs such as those with an articulating seat pan, angled seat pans, shaped seat cushions, or a variable-density foam cushion to limit excursion of the pelvis
- Alternative restraint systems – e.g., Y-belt systems, inflatable lap belt systems, etc.

To meet the 16-G test standard for seats in bulkhead rows, many seat suppliers try to limit the forward excursion of the test dummy. To accomplish this, many "front row" seats are already designed with alternative restraint systems and seat designs such as those mentioned above. To implement three-point restraints, the seat structural designs would likely have to be changed, making retrofit of these systems costly.

5.2.2 9-G Seats

Where the older 9-G seats were used, seat failure and seat tear-out from the floor was more evident. In all of the case studies except the 1991 Los Angeles accident, 9-G sustained mechanical damage. In 1987 in Denver, Colorado, a Continental Airlines DC-9 crashed on take-off due to icing. The aircraft broke apart in a manner similar to the 1989 Kegworth accident. There were 28 fatalities out of 82 people aboard. In the areas where there was fuselage and floor disruption, there was a massive compression of seats towards the forward sections. Many occupants were trapped in their seats, with 9 passengers dying from traumatic asphyxia after being crushed between rows of seats, debris, and aircraft structure. In 1994 in Charlotte, North Carolina, a US Air DC-9 crashed on landing in bad weather. Many seats were thrown clear of the aircraft or were crushed together near the front of the aircraft sections. While these accidents were severe, they were not of greater severity than the 1989 Kegworth accident. The dynamically tested 16-G structural seats would have increased survivability in these accidents.

In 1988, the FAA first proposed to retrofit older aircraft with 16-G dynamically tested seats. If this rule were to be implemented, lives would be saved and serious injuries would be prevented in partially survivable accidents. This ruling has been held up for a variety of reasons. It is clear from the accident data that delaying the implementation of this rule will likely lead to additional lives lost in partially survivable aircraft accidents. At a minimum, the rule should be established with the requirement that seats meet the dynamic structural requirements (with the exclusion of human injury tolerance) so that seats are required to withstand an otherwise survivable crash scenario. An additional alternative would be to incorporate an energy-absorbing device between the 9-G seat and the floor track. The device would not prohibit motion of the seat, but it might help to control that motion and thereby limit the number of seats that are torn out during the impact event.

5.3 ENERGY MANAGEMENT

The third requirement for increasing survivability is to manage the loads transferred to the occupant so that they are within the limits of human tolerance. If a survivable volume of space has been maintained, and the occupant has been restrained within that volume, injury and fatality can still result when loads transferred to the occupant exceed the limits of human tolerance. Excessive loading can occur through seat restraint loading, from impacts with the seat in front, or from impact by airborne debris. Although energy management involves all aspects of the aircraft interior design, most of this section's discussion will focus on the seats, the overhead bins, and the use of the brace position to help manage occupant vulnerability to injury.

In addition to structural performance requirements, the current 16-G seating standards include requirements based on occupant injury tolerances. Specifically, injury risk is assessed for the head striking the row of seats in front, femur compressive injury when the knees strike the seat in front, and lumbar spine injury in a vertical crash scenario. The seats in the 1989 Kegworth accident passed the 16-G structural requirements, but were not tested using the occupant injury criteria. The remainder of the seats involved in the case studies were not tested to these standards, so a direct evaluation of seat performance based on the new standard is not possible. However, it is possible to review the types of injuries observed and compare these to the types of injuries assessed by the regulatory standards to evaluate the appropriateness of the performance requirements.

5.3.1 Head Injury

The Head Injury Criteria, or HIC, is commonly used in other modes of transportation (particularly in the automotive industry) as a measure of head injury potential. The HIC was primarily developed as a means by which to assess the risk of serious head injury (skull fracture or brain injury) based on the impact of the head with a rigid object (Reference 14). A HIC value that exceeds 1,000 represents a 16-pct risk of serious head injury. The application of this standard to new seating systems is relevant, based on the case study results. Many head injuries noted in the study were from impact with the row of seats in front of the occupant, which is considered a rigid object as far as the requirements for the HIC calculation are concerned.

One item that the HIC criteria was not designed to measure is the resulting level of occupant consciousness. Unfortunately, there are currently no other criteria for consciousness that are generally accepted. In the 1989 Kegworth accident, 45 occupants suffered a loss of consciousness, contributing to the large number of occupants who were not able to egress the aircraft under their own power (Reference 15). Beyond the commercial aircraft environment, this issue of measuring consciousness is of concern to many parties, including the U.S. Navy who is concerned about occupants of helicopters losing consciousness in water impacts, and professional football in the U.S. where efforts are being made to improve helmet design to prevent players from being “knocked out” on the field. Injury measures, ranging from a reduced HIC value to a measurement of rotational head acceleration, have been discussed as possible ways to measure consciousness. Since egress is critical to occupant survival in many impact scenarios, the head injury analysis should include measurement of consciousness.

Overall, there are three recommendations for the use of the HIC criteria in seating system evaluation. The first is that the FAA requirements be revised so that HIC is measured across a 36-msec time interval, in a manner consistent with the automotive industry (Reference 16). While this will not directly impact occupant safety, it will allow research on head impact to be directly correlated between the modes of transportation, which, hopefully, will result in an increase in head injury protection in the future. The second recommendation is that the FAA and other interested parties stay aware of research into the measurement of unconsciousness. When standards are developed, these should be incorporated into the seating standards, particularly for crew and flight attendant seating systems.

The third recommendation is to include head injury evaluation into the proposed regulations for the 16-G seat retrofit. As these seats are brought up to the higher structural standard, they should also be brought up to the same human tolerance performance standards. While it is a higher priority to have the seat remain intact and attached to the floor, the structural improvement may not lead to improved survivability if the occupants cannot extricate themselves from the aircraft.

5.3.2 Lower Extremity Injury

Lower extremity injuries were extensive in many of the partially survivable accidents reviewed. Injuries to the feet, ankles, tibia/fibula, femur, and pelvis occurred in varying degrees in all of the accidents. Many of these lower extremity injuries were at least a partial result of seats becoming detached from the floor or failing entirely upon impact. Injuries to occupants in Areas II and IV of the 1989 Kegworth crash are of particular note, because they demonstrate injury mechanisms that might be prevalent in the new 16-G seats. In the 1989 Kegworth accident, the majority of passengers suffered AIS 2 or 3 lower extremity injuries, injuries that often prevented them from egressing under their own power. Only 18 of the 79 survivors had no lower extremity or pelvic injury. Lower extremity injury types included tibial/fibular fractures, sub-trochanteric (femur) fractures, and pelvic injuries, among others. Injury mechanisms included the “kick-up” type of injury where the tibia and fibula impacted the seat in front as legs flailed, pelvic injury from the occupant’s femur being driven back into the pelvis following knee impact with the seat in front, and femur fractures from bending moments generated as the occupant was loaded down and forward across the front seat tube. As only 14 of 79 survivors were able to extricate themselves from the wreckage, lower extremity injury would have led to a substantially larger number of fatalities had there been a significant fire or other post-crash hazard.

The current seat regulations require compressive femur loads to not exceed 2,250 lb in a horizontal 16-G dynamic test. However, testing in 1991 at the FAA Civil Aeromedical Institute (CAMI) revealed that even in “worst-case” scenarios of leg impact into a rigid barrier, femur compressive loads did not reach this limit (Reference 17). An accepted practice by the FAA foregoes the testing of new seat designs for femur compressive injury based on these CAMI results. However, as apparent in this accident, lower extremity injuries of several mechanisms are still occurring, and doubtless will continue to occur. Consequently, the test standard should be updated, and a review of other potential injury mechanisms and associated test procedures should be conducted.

Appropriate anthropomorphic test dummies (ATDs) and instrumentation are currently available to measure loads that relate directly to the injury mechanisms that were observed. A six-axis femur load cell is available for the Hybrid II that could help detect fractures related to bending of the femur across the seat tube. This improvement can be implemented quickly and easily. The Hybrid III ATD leg instrumentation includes 6-axis femur load cell, a 5-channel ankle/foot load cell, or a specially designed 20-channel lower leg. The newly developed THOR dummy has triaxial acetabular load cells to measure loads transferred from the femur to the pelvis, compressive load cells in the iliac notch to measure belt loads transferred to the top of the iliac area, a more compliant femur shaft for increased biofidelity, six-axis femur load measurement as in the Hybrid III ATD, a newly designed below-knee portion of the leg with upper and lower tibial load cells, and extensive foot and ankle instrumentation (Reference 18). Inclusion of pelvic loading measurement capabilities would require using the THOR ATD. However, measurements taken on the Hybrid III leg can also be made using the upper body and other instrumentation for the Hybrid II ATD, the dummy currently used for FAA certification testing. Simula recommends investigating increasing the amount of lower-extremity injury assessment performed for seat certification programs.

In association with reviewing the use of additional lower-extremity injury performance measures, further research is recommended into these injury mechanisms, particularly as related to the 16-G seat. Research information in this area, such as confirming the injury mechanisms demonstrated in the 1989 Kegworth accident, will lead to improved test standards and improved seat designs. To convey this information quickly to the user community, design and performance standards could be developed by an industry group such as the SAE Aircraft Seat Committee. Also, as with the head injury criteria, including any additional injury assessment requirements into the 16-G seat retrofit rule will help alleviate the risk of injury across the entire fleet.

As a final note on injury criteria, the injuries that tend to be the focus in the evaluation of an accident, particularly when there are fatalities from multiple extreme injuries, are those injuries that are most life threatening to the occupants. However, when one set of injury mechanisms has been alleviated, survivability is not guaranteed. Lower extremity injuries may not be a factor if multiple extreme injuries result from loss of seat attachment to the floor, or if a severe fire breaks out, not giving even uninjured passengers much time to egress. To increase survivability rates, more must be done than simply exchanging one mechanism of serious injury for another one. Therefore, it is important that all mechanisms of injury that could prevent occupant survival are analyzed and prevented when possible.

5.3.3 Airborne Debris

A cause of head injury in many accidents was impact from airborne debris. In White et al.'s report on the 1989 Kegworth accident, they reported a high incidence of head injury due to posterior head impacts from the overhead baggage bins becoming detached from their mountings (Reference 15). For occupants over the wingbox, posterior head injury was noted even when seat damage was minimal and only minor injuries were noted otherwise. Although there are only a handful of cases where impact from the overhead bin may have directly caused fatality, bin detachment is a significant issue, based on the frequency at which it occurs. Complications from displaced bins included head and upper torso injury (fatality, serious injury, loss of consciousness), hindrance from egress including entrapment, and increased seat deformations. On the other hand, in the 1988 Dallas/Fort Worth accident, several passengers used the debris to help them climb out of a hole in the fuselage on top of the aircraft. These passengers had otherwise limited means for egress. However, considering all of the accidents reviewed, only the passengers in the 1991 Los Angeles accident and the 1987 Detroit accident would not have benefited from improved bin attachment. Unquestionably, preventing bins from striking occupants and decreasing the amount of potential interior debris would improve occupant survivability.

Baggage bins are currently regulated under FAR 25.561, 25.787, and 25.789. FAR 25.561 is a general requirement that states that items of mass in the passenger compartment must be positioned so that if they are likely to break loose, they will not be likely to cause direct injury to occupants. Otherwise the equipment must withstand loads of 1.33 times the 9-G static load requirements (9 G forward, 3 G upward, 6 G downward, among others). It is very clear from the accidents studied that these requirements are inadequate to keep bins attached in partially survivable aircraft crashes.

There are several methods by which baggage storage on an aircraft can be delethalized. The first is to increase the attachment strength to better match the overall survivability level of the aircraft and the seats. Bin attachments might include energy-absorbing features to help control the motion of the bins and to allow for aircraft structural deformation. Other suggestions include alternative methods for baggage storage, particularly lower-level storage so that bins and baggage do not become head-level projectiles, or storage of baggage in alternative compartments, either in the main aircraft interior or in the aircraft body as done in some smaller aircraft. A less obvious means that might help reduce, but not eliminate the risk of head and upper torso injury is to increase the seat back height to enhance the “protective shell” around the occupant. This option is discussed in Section 5.3.4.

There are undoubtedly many creative suggestions that could also be implemented in future aircraft designs. If the overhead bins were removed, the weight savings could be potentially used to build up seat and floor structure to provide a secure means to store bags as well as to improve the floor and seat crashworthiness. There is research and development underway to consider methods of improving the overhead bin. If this research were extended to include consideration of the aircraft interior as a system, creative solutions that do not increase weight and perhaps have lower implementation costs could be developed.

5.3.4 Seat Back Height

In three of our case studies, injury patterns showed some evidence of shorter passengers receiving greater levels of protection than surrounding taller passengers. Also, passengers who “protected” other occupants received worse injuries than those they protected. In the 1987 Denver accident, a woman passenger commented that she felt her injuries were less severe than the person seated next to her because she was short enough to be protected by the seat back. The 5-ft 4-in. woman received only minor abrasions while seated in the center seat of a triple seat that was ejected from the aircraft. The passengers seated on both sides of her received serious injuries, including head and torso injuries. The woman appears to have been shielded from injury both by her seat back and by the passengers to each side of her.

The concept of smaller-sized occupants being more protected was also evidenced in the 1989 Sioux City crash in which all of those who survived in a rear section of the aircraft were 5 ft 8 in. tall or less, with those taller occupants in surrounding seats predominantly suffering fatal head injuries. The head injuries were potentially caused by detached bins and other structures. Finally, in the 1987 Detroit accident the only survivor was a 4-year old girl. While it is only speculation, one possible explanation for her survival is that her short stature and the presence those seated around her shielded her from fatal injury.

While air travel is not like a carnival ride that can limit participation to those of a certain height, this issue should be considered in greater detail. A small research study on the trade-offs between increasing occupant protection and operational issues such as not being able to view safety briefings could be conducted. Additionally, an industry group like the SAE Aircraft Seat Committee could determine appropriate seat back height or other design standards to increase occupant shielding. While this may prevent head injury in a limited number of scenarios, this solution is relatively inexpensive and could be easily implemented on new seats.

5.3.5 Crash Brace Position

One method currently utilized to manage the vulnerability of occupants to the loads transferred to them is a crash brace position. A crash brace position is generally defined as a bent-over position such that the occupant’s head is placed as far forward as possible. The objective is to minimize the relative velocity between the occupant’s head and hazard that the head would strike. There is substantial evidence of head and face strikes with the row of seats in front of them when occupants were not braced due to lack of warning of the accident. However, information in the accident reports was insufficient to draw direct conclusions in regards to the most appropriate position or the specifics of what injuries occur in partial or “improper” braced positions.

The NTSB report from the 1990 Cove Neck accident reports that passengers were not given warning of the crash so that passengers were not instructed to take a brace position (Reference 19). Based on their review of injuries sustained, the NTSB believed that had passengers taken a brace position, their injuries would have been less severe. White, et al. (Reference 15), studied the effects of the brace position on injury in the 1989 Kegworth accident. They determined that passengers who adopted a brace position received significantly less severe head injury, concussion, and injuries from behind than passengers who did not adopt a brace position. In this instance, passengers were told to “prepare for crash landing” but were not given more detailed instructions about the appropriate position to adopt.

While it is clear that a brace position can help alleviated some injury, there is often insufficient warning of the accident and thus insufficient time for the passengers to be told to take a brace position or to be instructed on a proper brace position by the crew. In an internal Simula investigation, the sequence of aircraft accidents was evaluated to determine if there was sufficient time available for crew to instruct occupants to take a crash brace position (Reference 20). The NTSB abstracts from the Part 121, 129, and 135 accidents occurring in the period between January 1983 and September 1997 were evaluated. The results of this study indicated that in 75-80 pct of the accidents, there was insufficient time available for crew to provide passenger instructions regarding adopting a brace position.

Simula recommends that additional efforts be made to determine the best position for bracing and the best methods for communicating this information to passengers. Brace position considerations should include leg placement as well as head placement, and alternative positions for short seat pitches, as well as for short, tall, obese, and other special occupants.

5.4 EGRESS AND ENVIRONMENT

The final critical element to surviving an aircraft accident is the ability to safely egress the aircraft once the impact has ended. Even if an occupant has survived the initial impact with injuries that allow them to egress the aircraft under their own power, there remain a number of challenges to occupant survivability. Challenges include the usefulness of exits and exit slides, the ability to locate exits in the dark and amidst debris, the dangers from fire and smoke, and other aircraft exterior hazards such as water or extreme weather conditions.

5.4.1 Aircraft Exits and Egress

The ability to egress from the aircraft after an accident has occurred is crucial to occupant survival. Planned egress occurs through aircraft exit doors and down emergency evacuation slides. Factors which can make some or all of the exit doors unusable include aircraft structural damage, aircraft inversion, internal hazards such as damaged seats and detached overhead bins, and external hazards such as blockage by terrain, fire, and deep water. Unplanned methods for egress usually involve exiting through breaks in the aircraft fuselage or rescue crews having to cut through the aircraft skin to extricate trapped passengers.

Planned passenger exits were limited in many of the accident cases studied, including the 1991 Los Angeles accident in which fire at some exits made them unusable, the Dallas/Fort Worth accident in 1988 in which 9 passengers died from smoke inhalation behind a door that they could not open, and the 1990 Cove Neck accident in which at least 2 of the exit doors were jammed from structural deformation. Planned exits should be capable of maintaining their integrity and operational effectiveness in partially survivable accidents. This includes sufficient attention to volume flow through partially obstructed exits with a “turbulent” crowd, and when most other exits are obstructed. Operational issues such as instructing that the exit door to be placed inside the aircraft instead of outside the opening should also continue to be reviewed.

In other accidents such as Charlotte and Denver in 1987, many of the passengers exited through breaks in the fuselage when aircraft damage was so extensive that the breaks became the easiest or the only choice for egress. Passengers in the 1987 Denver and 1988 Dallas/Fort Worth accidents indicated that they used baggage and bins to help climb out of breaks in the aircraft. However, exiting through breaks in the aircraft produces injury risks from falls from heights or unsupported structures, contact with hot or sharp-edged metal, and dangers from an assortment of items including wiring harnesses and jet fuel. Survival should rely upon planned methods of egress instead of upon chance. As mentioned in Section 5.1 above, the use of controlled breakage areas would help to delethalize aircraft egress when structural damage or other factors prohibit the use of planned exits. Alternatives might include increasing the number and location of planned exits so that structural damage at certain places in the aircraft (e.g., fore and aft of the wing box) does not cut off access to planned exits

5.4.2 Fire/Smoke/Toxicity

When a post-crash fire occurs, fatality and injury can result from direct exposure to the fire or from the smoke produced by fire. Smoke inhalation is one of the leading causes of fatality in partially survivable aircraft accidents, causing 35 fatalities in the 1989 Sioux City accident, 9 fatalities in the 1988 Dallas/Fort Worth accident, and 19 fatalities in the 1991 Los Angeles accident. Although fires do not occur in all partially survivable accidents, they can lead to massive casualties in otherwise survivable accidents. The ability to egress the aircraft and the time required for egress are both critical to the occupants' survival.

The 1988 Dallas/Fort Worth accident was caused by improper configuration on take-off. Passengers had no warning of the accident, but overall the crash was relatively mild. Few seats showed mechanical damage and there were no fatalities due to blunt trauma injury. The nine passengers who died from smoke inhalation were found around the rear door of the aircraft. The floor of this section of the aircraft ended up slanted. Apparently the passengers were unable to open the exit before being rendered unconscious by smoke. There were surviving passengers seated in the same area who egressed through a forward exit. Had there been more time available, the passengers headed towards the rear door could have reversed their course and used a different exit to safely egress the aircraft.

In the 1991 Los Angeles accident studied, a Boeing 737 collided during landing with a Metro II commuter aircraft holding on the runway. All 12 occupants aboard the Metro II were fatally injured due to loss of occupiable space. As conditions on the Metro II were considered non-survivable, this study has focused on the 737. Of the 6 crew and 83 passengers aboard the 737, 19 passengers and 1 flight attendant were fatally injured due to smoke inhalation, while 11 passengers suffered serious injury from smoke inhalation, thermal burns, and injuries sustained upon evacuation. The aircraft remained relatively intact with the exception of the cockpit area. The pilot suffered fatal multiple extreme injuries and the co-pilot suffered a fractured pelvis from the crush of the nose area. In the passenger area, the aircraft floor and seats stayed relatively intact. A fire broke out before the aircraft came to a rest, quickly filling the cabin with thick black smoke. The acessibility of exits was hampered by the fire on the left side of the aircraft. The L1 exit was non-operable due to the fire outside of the aircraft. Two or three individuals egressed through a right front service door, from which the slide did not deploy. Most passengers aft of Row 16 egressed through the right rear door. The left rear door was operable but not used. Two passengers egressed through the left overwing exit, with the remainder of the surviving passengers egressing through the right overwing exit. Passenger flow through the right overwing exit was hampered by a number of factors. One of the passengers seated next to the exit panicked and could not open the door. Slowing the process further was an altercation that broke out between passengers attempting to egress. Egress was also complicated by the exit door, which had been placed on the seat in the exit row. A seat back pushed over the door resulted in a partial blockage of the exit. On the positive side, the floor track lighting was effective in leading some passengers to a useable rear exit. While there were several factors that conspired against passenger egress in this accident, the bottom line was that there was insufficient time available for the given evacuation plan of the passengers. Either the time for passenger egress in a fire needs to be extended, or the operation and design of the exits need to be re-evaluated.

Since airplanes require large quantities of fuel, it may not be possible to eliminate fuel-fed fires. A reasonable goal, however, is to suppress the spread of fire and decrease the generation of toxic smoke to give surviving passengers additional time to egress. The FAA and other parties have been investigating fire suppression systems to contain fire and suppress smoke and fumes for an extended period of time, the use of alternative materials that burn more slowly and with fewer toxic emissions, and the flow of passengers out of planned exits (Reference 21).

One technology that is commercially available for extending the time to egress is the smoke hood. Presumably a passenger could don the smoke hood, which provides them with a source of clean air to increase the time available for evacuation. Like taking a brace position, the effective use of smoke hoods would require additional passenger training and would likely be most effective when the chance of an emergency landing is known prior to the event. However, since time can be critical in egress, the time taken to don the smoke hood might add to the overall time taken to clear survivors from the aircraft. While smoke hoods might provide a near-term measure of safety or an additional safety procedure that individuals may choose to adopt, a long-term solution should include designed-in methods for safety such as reducing the flammability and toxicity of aircraft materials, fire suppression systems, and improvements in designed-in methods of egress.

5.5 CHILD PASSENGERS

One special population of aircraft passengers consists of infants and small children. Current FAA regulations allow children under 2 years of age to fly unrestrained while seated in their parents' laps. Basic knowledge of crash safety and common sense tell us that this is not a safe way for infants to travel. Crash protection requires occupant restraint. Even the strongest parent cannot hold onto their child during a crash event. In fact, even in relatively minor accidents, parents are not able to restrain their lap-held infants. Besides having inertial forces pull the infant from the parent's grasp, an additional risk is that the child can become trapped between the adult and the seat in front of them, potentially leading to the child being crushed by the parent's body.

Lap-held children were passengers in many of the aircraft accidents that were investigated. Chance seemed to have played a large role in determining survivability for these children. In the 1987 Detroit crash and in the 1989 Kegworth crash, the size of a small child may have played a role in their survival as the seat back and surrounding structure may have provided protection against debris and other strike hazards. However, lap-held children have not fared as well in other accidents. Four lap-held infants were aboard the 1989 Sioux City crash. Three of the infants were aboard a section of the aircraft that sustained relatively low impact forces. Each of these three infants survived the crash, but one infant was carried out of the aircraft by another passenger after the parent lost control of the child. The fourth infant died from smoke inhalation, not impact forces, after being pulled out of their parent's grasp by inertial forces. The parents and flight attendants followed standard procedure, having the parent hold the infant on the floor of the aircraft for the emergency landing. This braced posture was not sufficient to allow children to be restrained in their parent's grasp.

Two lap-held children were aboard the DC-9 that crashed in Charlotte, North Carolina in 1994. One survived the crash, but was seated in its own seat during landing, although the means, if any, by which the child was restrained to the seat were not clear from the report. The second infant received fatal injuries, again after the mother was not able to hold onto the baby during the crash event. In an interview with the mother following the accident she said, "During the impacts, the baby went flying in front of me – I tried to hold her and I couldn't. They told me I could hold her on my lap. I would have paid for her to sit in a seat… The man said that she did not need a seat because she was under the age of 2". Similar situations were noted by in the 1990 Cove Neck and 1987 Denver accidents. In the 1990 Cove Neck accident there were 10 lap-held children aboard, with some infants reportedly belted in with their adult passenger. Parents reported that they were not able to maintain a grasp on the infants, nor were they generally able to locate the infants in the darkness following the impact.

The 1997 Gore Commission report (Reference 22) and the NTSB (Reference 23) have both recommended the restraint of children under the age of 2. In April of 1998, the FAA sought public comment on an advanced notice of proposed rulemaking on this topic (Reference 24). Based on the results of Simula's analysis, Simula encourages swift action in requiring appropriate restraint for all children under the age of 2 on aircraft. Appropriate restraint entails both the requirement that children under the age of 2 are restrained during take-off and landing as are all other passengers and that appropriate regulations are in place so that child seats are designed and tested to aircraft-specific criteria.

Unfortunately, even if children are required to be restrained, determining the appropriate type of restraint may not be a simple task. Testing at the FAA Civil Aeromedical Institute (CAMI) has provided information regarding the safety of children in airline seats in the event of a crash (Reference 25). The testing demonstrated that child restraint systems (safety seats) which met the FMVSS 213 requirements were not necessarily safe for aircraft usage. Problems with fit, installation, and adjustment of the child seats were noted. Aft-facing seats, those typically suitable for children under 1 year of age, performed acceptably, while other types of seating – forward facing, booster seats, and harness systems - did not provide adequate child protection. Harnesses (“belly belts”) and booster seats are already banned by the FAA as the standard lap belt system provides larger children with better protection than these systems.

Additionally, the National Highway Traffic Safety Administration (NHTSA) recently issued a final rule regarding child restraint design for use in automobiles (Reference 26). Since there is a high rate of misuse of automotive child restraints in automobiles, NHTSA, automakers, child seat manufacturers, and other interested parties worked together to improve child restraint in vehicles. The results of their efforts will change the way that child restraints are attached to automobiles. The seats will have a positive connection to the vehicle frame through a connection in the seat bight. This connection will be distinct from the standard automotive seat belt. Additionally, top tether straps will be required for forward-facing seats. While these improvements will help restrain children better in automobiles, which are their primary means of transportation, they are currently inconsistent with improved child safety on aircraft. Based upon the changing automotive child restraint standards and upon the results of the CAMI study, Simula Technologies also recommends further evaluation of the design and performance standards for child restraints in aircraft. However, the only sound practice is to provide small children with an equivalent amount of protection as their older flying companions and to the provide child's parents with complete information regarding the use of child seats on aircraft and of the dangers of children not being restrained.

5.6 TURBULENCE

Turbulence is the leading cause of injury in non-fatal accidents. The FAA estimated that 30 pct of all passenger injuries in the last 5 years can be attributed to turbulence (Reference 27). In Simula's accident database study, there was found 1 fatality, 139 serious injuries, and 457 minor injuries attributed to turbulence in 103 accidents. The vast majority (85 pct) of these injuries occurred during the cruise phase of flight, while 13 pct occurred during approach. Those injured were fairly well divided between flight crew and passengers. Lower-extremity injuries dominate, particularly to crew and passengers who were standing during the turbulence event. However, seated passengers, both restrained and unrestrained, also suffered injury. Other types of turbulence injury experienced include head injury and clavicular fractures from falls, head injury from being struck by airborne debris, and burns from spilled coffee.

The FAA has initiated programs to help reduce these injuries. The FAA supports a program entitled “Turbulence Happens” to increase public awareness of the need for passengers to fasten their seat belts during all stages of flight. As many instances of turbulence occur with no warning, additional technology developments in this area focus on the development of radar systems that provide advanced warning of atmospheric turbulence (Reference 28). Advanced warning will help decrease injury, particularly to flight attendants who stand during flight as part of their job requirements. Public awareness of the need for wearing seat belts and advanced warning of turbulence, if it is communicated to the passengers, should provide a significant improvement in turbulence injury rates.

Additionally, some of the same technologies that are recommended for improved crash safety can also help to reduce the severity of turbulence-related injuries. First, as the FAA points out in their "Turbulence Happens" campaign, restraint is essential. Occupants should be encouraged to wear their seatbelts in a reasonably snug manner for the duration of the flight. In addition to preventing turbulence injuries, this will also help ensure fastened restraints in the event of an emergency scenario. Delethalizing seat backs, improving overhead bin attachment, and improving baggage storage in the overhead bins should also help reduce turbulence injury.

5.7 OTHER ISSUES

Although it was somewhat beyond the scope of this investigation to assess operational issues related to flight crew and emergency-response personnel, the action, or inaction, of these parties often made a critical difference in occupant survival. For surviving passengers, the nightmare of an aviation accident does not end when they egress the aircraft. Passengers often have to wait for emergency-response crews to transport them to hospitals or to areas of safety. In the case of the 1989 and 1992 Flushing Bay accidents, passengers found themselves waiting for rescue in deep water. Factors such as flight crew and emergency-response personnel training, and airport and local emergency-service disaster plans should not be overlooked when determining how to improve the overall survivability of aircraft accidents.

In the 1989 Kegworth accident, quick emergency response was responsible for the survival of many passengers with head injuries. In contrast, following the 1987 Denver accident, there was evidence that at least one trapped passenger survived the initial impact but died during the multiple-hour wait to be extricated. It is not possible to know whether or not this person would have survived with faster treatment; however, he was able to communicate with fellow trapped passengers for a period of time after the impact. Even in accidents that occurred on or near airport grounds, several hours were often required to extricate and transport passengers for treatment.

Well-trained flight attendants have often made a difference in occupant egress. In the 1988 Dallas/Fort Worth accident, there were several flight attendants on board the aircraft “dead-heading” back to other cities. The statements of surviving passengers clearly indicated that these off-duty flight attendants were instrumental in helping passengers escape the aircraft. In other accidents, flight attendants were responsible for finding and leading passengers toward usable aircraft exits or through holes in the aircraft that were sufficient for egress. However, although flight crew responded reasonably well while aboard the aircraft, they were often lost as to how to best deal with injured passengers following egress.

6. CONCLUSIONS AND RECOMMENDATIONS

Full and effective implementation of safety improvements requires several key steps, which are identified in Figure 13 (Reference 29). The identification of injury mechanisms in the field is only a part of that process. Effective implementation requires development of the preventative technology, evaluation and demonstration of the technology, creation and implementation of appropriate regulatory drivers or regulatory evaluation of the technology, direct measurement of field results to determine the relative effectiveness of the new technology, modifications and improvements of the technology, and the continued review of injury mechanisms to identify new and/or unexpected challenges to occupant survival. The purpose of this study was to identify mechanisms that produce injury and fatality in partially survivable accidents and to prioritize the technologies that could mitigate these mechanisms of injury. These actions constitute only a small part of the process that must occur for a safety improvement to be effective at reducing the number of fatalities and the number of fatal accidents.

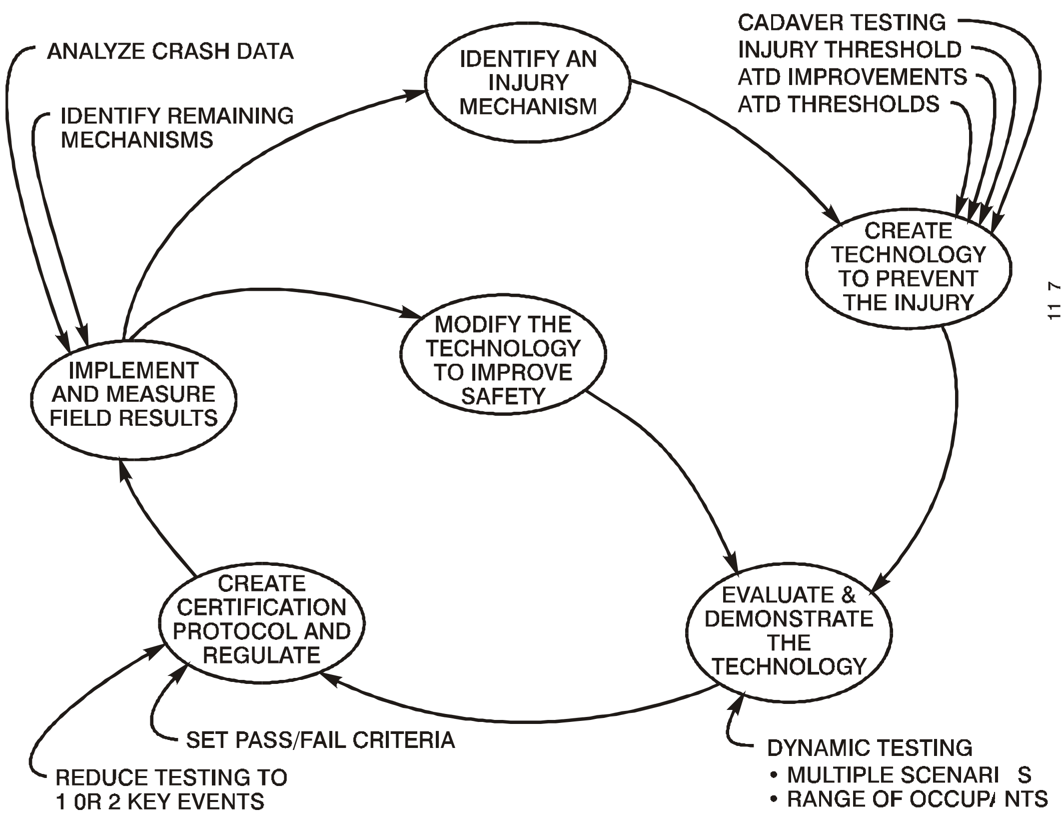

Figure 13.
The flow of safety technology development and implementation (Reference 29).

6.1 BASIS OF THE STUDY

The detailed case studies represent transport category aircraft accidents that occurred over the time period from 1985 to 1994. Accidents studied were considered partially survivable, based on their having at least one survivor and one fatality on board the aircraft. Partially survivable accidents were used so that the experiences of survivors and non-survivors in the same accident could be compared to determine the causes of injuries and fatalities. Once the causes of injury and fatality are understood, mechanisms by which to mitigate them can be developed.

A total of 11 case studies were performed. Even though this is a relatively few number of accidents, they reflect the types of accidents usually encountered. Scenarios included take-off, landing, fires, and aircraft-to-aircraft accidents. The range of structural survivability was covered with the 1991 Los Angeles accident having very little structural damage while the 1989 Kegworth accident pushed the limits of structural survivability. The 1987 Detroit accident was included in the study since there was one survivor, even though the accident is probably best classified as non-survivable. The 11 cases selected represented about 75 pct of the accidents available for review once non-crash events such as explosive decompression were removed.

The database portion of the study helped to put the results of the case studies into a broader perspective. By focusing on injury-producing accidents, the database review highlighted the high prevalence of turbulence-related injuries. While this was not a focus of our study, some of the proposed actions to improve crash survivability may also help decrease the risk of injury in turbulence events.

6.2 LIMITATIONS OF THE STUDY

The primary limitation of this study is that publicly available accident data is largely focused on the cause of the accident, and not the cause of injury. Because of this focus, data and analysis related to occupant survival is often limited. It is usually difficult, if not impossible, to fully reconstruct what the passengers experienced and what lead to their injury. For example, the full tie-down chain of the accident must be considered one wishes to determine where safety improvements will have the most benefit. Details of seat damage cannot stand apart from aircraft structural and floor damage when assessing occupant restraint. Additionally, medical and autopsy data is critical. To understand how injuries occurred, it must be known if a head injury was to anterior or posterior portions of the head and how that injury corresponds to damage seen on the adjacent overhead bin or the seat in front of the passenger. If occupants are identified only by seat number and vital statistics (e.g., age, height, weight, etc.), then personal identities can be protected.

The most productive reviews were for those accidents in which Simula's review team included a person who had been at the site of the accident. Those on-site were able to recollect certain features of the accident that were not reported in detail in official reports but that were necessary to the understanding of the injury-producing sequence.

Following discussion with members of the National Transportation Safety Board and others who have participated in accident investigations, it seems that appropriate procedures for collecting information are already in place. Additionally, when the accident reports are taken in sum, most of the data that this study was interested in appears to have been collected. Unfortunately, this information is not fully conveyed in each accident's final report. The type of information needed to perform this evaluation includes detailed injury and autopsy information, detailed seat damage and deformation measurements and photographs, damage and deformation information for other interior structures, detailed descriptions of structural deformation in the passenger areas, passenger and witness interviews that directly address interior safety and egress questions, and egress patterns, including which exit each person used. Additionally, photographic evidence is very helpful when interpreting data from written records.

The data available was not sufficient to develop differential, quantitative conclusions about the efficacy of various safety technologies. In some cases, the cause of injury was very clear –either based on the detailed evidence or based on a thorough analysis performed by someone who had been at the accident site. In many other cases, the cause of injury was difficult to determine conclusively based on the information available. For example, a passenger's head injury may be described, but it was not clear whether the injury occurred from contact with the seat in front, from impact by airborne debris, or if it was due a fall or other event upon egress. If a detailed description of the injury and the damage to interior components could be obtained, and a thorough interview with the passenger could be conducted, the cause of injury could be determined with some degree of confidence. Although medical and biomechanical experts have contributed to the evaluations of injury mechanisms presented in this report, the results are still a professional judgement and are often drawn from incomplete information.

The nature of the case study approach also limited Simula's ability to make forward projections about the technologies that will reduce fatalities in the future. As an example, this study did not investigate accidents where there were no survivors. One of the methods by which to reduce the fatal accident rate is to expand the range (velocity and acceleration envelope) of survivable and partially survivable accidents. Since this study did not investigate accidents currently identified as non-survivable, most recommendations made will be more likely to eliminate or reduce the number of fatalities in accidents which are already in the "survivable" range, rather than to expand the envelope of survivable crashes. To expand the envelope of survivable crashes, more crashes similar to the Detroit accident, i.e., accidents just outside the survivable envelope, should be studied in great detail. However, this group of accidents is likely to be very small. Additionally, the research conducted in this study reflects the transport fleet as it was in the 1980's and early 1990's. Changes in technology, aircraft equipment and aircraft operations will change the nature of some accidents in the future. Although future changes were not studied explicitly, potential effects on aircraft accident and injury scenarios will be discussed in the Recommendations section.

6.3 TECHNOLOGY SUMMARY

The technologies recommended from the case study evaluations are summarized in Table 2. This list is meant to serve as a highlight of the technologies and issues discussed in the accident case studies. It is not meant to serve as an all-inclusive listing of the various options available to reduce fatalities or to reduce the fatal accident rate. In many cases, there are multiple technical approaches that can meet the same basic need. In these cases, Simula has sought to define the need instead of defining which specific technologies would meet that need. For example, the need for increased pelvic restraint can be met by the use of inertia reels, powered haul-back systems, articulating seats, alternative restraint geometries, three-point restraints, variable-density cushions, and new seat designs. The intention is not to promote the use of one method over another, as that should remain the decision of the seat designer and the seat customer, but to present the available alternatives to mitigate injury.

Additionally, there are some inherent trade-offs and synergies among the technologies. Providing for one set of needs may increase or decrease the need for remediation in other areas. For example, some of the methods to improve occupant restraint, such as the use of three-point restraints, could also serve to reduce the need to delethalize seat backs. If the occupant's head was no longer able to contact the seat in front of them, then the lethality of the seat back may no longer be an issue.

Table 2.
Summary of recommended technologies, research and regulatory actions

OCCUPIABLE SPACE **Structural Deformation** Control the break-up and crush of the fuselage to maintain a survivable occupant volume Remove seating along breakage areas Remove passenger seating from dangerous areas
RESTRAINT **Floor Structure** Increase the design and performance requirements to more closely match human tolerance standards, to provide alternative load paths and to account for out-of-floor-plane loading **Seat Structure** Limit loads transferred to the floor track to maintain seat attachment Enact a retrofit rule for structural requirements that is compatible with the 16-G seat retrofit rule Increase occupant restraint within the seat Incorporate methods for torso restraint Improve pelvic restraint
ENERGY MANAGEMENT **Delethalize Seating Systems** Research potential lower-extremity injury patterns with 16-G seating, and revise the performance and design standards so that lower-extremity injury risk is appropriately assessed and mitigated Delethalize the seat backs so head contact does not produce a serious head injury risk Include injury assessment criteria in the 16-G seat retrofit rule Research trade-offs involved in increasing seating height and 'compartmentalization' of passengers. If appropriate, develop industry design standards associated with the research findings **Delethalize Storage of Carry-on Baggage** Increase the performance requirements to match conditions experienced in partially-survivable accidents, similar to dynamic 16-G requirement Incorporate improved methods of overhead bin attachment Develop alternative methods for storage of baggage Improve methods of restraining baggage within the overhead bins
EGRESS AND POST CRASH SURVIVAL **Egress** Improve the exit door integrity and function in relatively severe, but survivable crashes Continue research into operational issues surrounding egress. Revise the requirements to implement research findings Increase the number of planned exits and improve the distribution of exits along the aircraft Investigate other means by which to extend the time available for egress (e.g., smoke hoods) **Fire and Smoke** Continue the research and implementation of fire suppression systems Continue the research and implementation of reduced material flammability and toxicity Continue the research and implementation of crashworthy fuel systems
Child Passenger Protection Require all children under the age of 2 to be restrained during take-off and landing Research and revise seat design standards so that aircraft seats can appropriately restrain children seated in automotive-approved child seats

6.4 CAUSE OF INJURY SUMMARY

This section summarizes the primary causes of injury in each case study, based on the framework presented in Table 2. Information is summarized in Table 3. The first thing to note is the frequency with which structural deformation played a critical role in occupant survival. This finding is not surprising since, when the structure fails, the occupant is likely to be crushed or lose restraint and be thrown against a rigid object. Aircraft structural integrity does not currently approach the limits of human tolerance to injury by acceleration; therefore, it is quite possible that an occupant could withstand the deceleration of the crash, only to crushed or battered to death by a secondary impact. When structural integrity fails, injury includes traumatic asphyxiation and multiple extreme injuries.

Table 3.
Summary of injury mechanisms by technology area for each accident case study

		Restraint			Energy Management		Egress		
Accident Description	**Occupiable Space**	**Floor**	**Seat**	**Occupant**	**Seating**	**Baggage**	**Exits**	**Fire, Smoke and Toxicity**	**Child Passenger Protection**
1989 Sioux City, IA	A			B	B/P	B	B	A	A
1988 Dallas/Fort Worth, TX							A	A	
1989 Kegworth, England	A	A	B/P	B	A	A		P	
1991 Los Angeles, CA							A	A	
1992 Flushing, NY	A	B	A		B	B		B	
1985 Dallas/ Fort. Worth, TX	A							A	
1987 Detroit, MI	**				P				
1987 Denver, CO	A	A	A		B	B			A
1994 Charlotte, NC	A	A	A		B	B	B	A	A
1989 Flushing, NY	A								
1990 Cove Neck, NY	A		A		A				B

A = Major cause of injury or fatality – high number of injuries and fatalities, and/or clear cause
B = Minor cause of injury or fatality – low number of injury and fatalities, and/or probable or secondary cause
P = Preventative benefit clearly demonstrated
** = Accident was non-survivable
Blank = Not relevant or insufficient information was available to determine causal relationships

The role of floor deformation in producing injury was often hard to determine. In some cases, it was not clear where restraint failure occurred – at the floor, the floor track, or the seat. Also, it was often not clear whether floor failure was based primarily on floor design or on the limitations of the entire aircraft's structural integrity. Despite confusion over the cause of failure, injury patterns could often be directly correlated with the amount of floor failure. The predominant injuries in these areas were traumatic asphyxiation and multiple extreme injuries. Severe lower-extremity injuries were also often noted, but these were not likely to be the principle cause of death. Establishing the details of the restraint chain failure is one area that would benefit from a refocused crash investigation procedure.

Restraint of the seat failed when the seat pulled out of the floor track or when the seat suffered severe deformation or damage due to crash loading. The high incidence of seat restraint failures in some accidents may be at least partially mitigated in the future by the use of 16-G seating. When the seat restraint fails, injuries to the head, torso, and lower extremities often result. Crushing injuries to the torso and extremities also occur when failed seats literally pile on top of each other. The number of fatalities and the effect of the seat on occupant survivability could be significantly decreased if 16-G seats were required to be retrofit into the entire fleet instead of just being used on newly type-certificated aircraft.

It might seem contrary to common sense that the restraint of the occupant did not factor highly in this investigation. This apparent paradox occurs because other failures in the tie-down chain mask the effects of occupant restraint. For occupant restraint to significantly contribute to occupant survival, the tie-down chain linking the seat to the aircraft structure must be maintained. As there was often too little information to assess the effect of the occupant restraint, the focus was instead placed on energy management on the seat itself. Injuries from impact with the seat in front included severe lower extremity injury, pelvic injury, head, facial, and torso injuries. These injuries can be mitigated both through improving the restraint of the occupant within the seat and by delethalizing the contact between an occupant and the seat in front of them. A tighter coupling of the occupant to the seat will mitigate injuries from contact to surrounding objects. Delethalization of surrounding objects is necessary when tight coupling of occupant to seat does not exist, as with the current two-point restraint, or when that coupling fails.

While small children make up only a small fraction of the flying population, the majority of lap-held-child fatalities in the accidents studied could have been prevented with appropriate child restraint, as children who died were often seated in areas where restrained adult passengers survived. When the child's restraint relied upon the parent's grasp, the survival of the child became a matter of chance. Fatal injuries typically occurred from blunt trauma and from smoke inhalation. While the proper restraint of children will not have a great effect on the overall number of aircraft-related fatalities, the mechanism by which children could be protected is so obvious and the solution is so readily available, that it should not dismissed based on the small number of fatalities prevented.

Another common event in these aircraft accidents was the loss of overhead bin structural attachment. However, with the exception of an explicit investigation of the effect of the overhead bins on injury following the 1989 Kegworth accident, the direct effect of the overhead bins on occupant injury was hard to decipher. In a number of accidents, occupants appeared to have suffered head or upper torso injury, or had their egress options limited by the presence of detached overhead bins and freed baggage. The severity of injury potentially related to the detachment of overhead bins ranged from fatal to minor. In order to draw a direct link between overhead bin attachment and injury, detailed descriptions of the damage to the bins and details of occupant injury would be required. The correlation was additionally hampered by severe damage to the overhead bins because of fire and rescue operations.

The effects of post-crash fire and the ability of the occupants to egress the aircraft are strongly tied together. In accidents where there was no post-crash fire, the time taken to egress and the exits available became much less of a factor. When fire was a factor in an accident, it often led to multiple fatalities, more often from smoke inhalation than from thermal injury. Transient fire balls and thermal exposure provided less overall risk to occupants than did smoke. When fire was not a significant factor, egress injuries tended to be relatively minor – leg injuries and lacerations were noted most often.

The large effect of lower-extremity injuries seen in the 1989 Kegworth accident is analogous to increases in lower-extremity injuries seen with the use of air bags in automobiles. In severe auto accidents, fatal head and chest injuries are now being prevented. Correspondingly, more severe lower extremity injuries are being reported. These injuries occurred before the use of air bags, but were relatively less important than the fatal head and chest injuries. To realize reductions in the number of fatalities, not only must the most obvious problems of seat restraint and fire prevention be solved, but the entire system of occupant protection must be examined.

6.5 RECOMMENDATIONS

Tables 4A - 4C summarize recommendations according to the following categories: Research and Development, Regulatory Activities, Recommended Investigation Activities, and Other Activities. Research and Development Activities represent those technology needs for which a specific technology is not currently available. Regulatory Activities represent areas for which technologies are either currently available or can readily be made available. Recommended Investigation Activities are those actions that would make analysis of safety improvements easier or faster in the future. The final category of Other Activities crosses functional boundaries and requires participation from all those involved in aircraft safety. All activities are prioritized as either critical, high-priority, or moderate-priority. This categorization was made subjectively, based on the potential to reduce fatalities in a partially survivable accident or upon the ability to expand the range of accidents that are considered survivable. Activities categorized as critical are those that will provide a substantial benefit to passenger safety. High-priority activities provide a large-to-moderate benefit. Moderate-priority activities provide a moderate-to-low benefit or aid the investigation and implementation of new safety features. There are many activities and technologies that could provide minor benefits, providing either a low benefit or being applicable in only a limited percentage of scenarios. Simula did not seek to capture all of those minor options, but rather focused on those expected to provide the most benefit. Research and regulatory activities were further subdivided into near-term and long-term activities. Near-term activities are those that could be performed in a short time frame (1-3 years) while long-term activities will likely require a more substantial amount of time (3-10 years) to implement.

6.5.1 Near-Term Research Activities

The near-term Research Activity deemed most critical was the evaluation of lower-extremity injury patterns and the development of appropriate mitigation schemes to address these lower-extremity injuries. Simula's data sample only included one accident with 16-G structural seating. In that accident, the number of serious lower-extremity injuries and the resulting effect

Table 4A. Recommended Research And Development Activities		
Subjective Assessment of Priority	**Research Activities**	**Comments**
	<u>Near-Term Accomplishment</u>	
Critical	Investigate lower extremity injury patterns and develop appropriate design, test, and performance requirements	Critical to ensuring effectiveness of 16-G seating and ability to egress following a severe accident
High	Research application of automotive child seat technologies to aircraft seating	To ensure proper restraint of children, aircraft seats must take advantage of improvements in automotive child seats
Moderate-to-High	Investigate efficacy of increasing seat back height and occupant compartmentalization	Moderate benefit to survivability could be achieved easily on new seating systems
Moderate	Research best occupant brace position and improved methods for informing passengers regarding this best position	Implementation of new brace positions is relatively cheap and easy, and could benefit passengers on all aircraft types
	<u>Long-Term Accomplishment</u>	
Critical	Determine methods for increasing aircraft structural integrity and/or for controlling the break-up of the fuselage	Provides the highest potential for decreasing the fatal accident rate by expanding the range of survivable accidents
Critical	Determine methods for improved floor structural integrity	Provides the second-highest potential for decreasing the fatal accident rate by expanding the range of survivable accidents
High	Continue research on fire-suppression systems	Hard to achieve and potentially costly to retrofit, but the benefit is large
High	Continue research on reducing flammability and toxicity of materials	Large benefit for new aircraft, potentially costly to retrofit
High	Continue research on crashworthy fuel systems	Hard to achieve and potentially costly to retrofit, but the potential benefit is large
High	Continue research on operational issues surrounding occupant egress	Operational improvements could be implemented faster than fire suppression and crashworthy fuel systems become available. May be relatively cheap to implement.

Table 4B. Recommended Regulatory Activities		
Subjective Assessment of Priority	**Regulatory Activities**	**Comments**
	Near Term Accomplishment	
Critical	Enact retrofit rule for seating systems, preferably to include human tolerance criteria	Large potential benefit from seat structural upgrades. Moderate benefit from including human tolerance criteria. Technology is readily available.
Critical	Enact requirements for dynamic performance of overhead bins for new and existing aircraft	Large potential benefit. Injury from detached bins could substantially worsen given current types of baggage and usage of bins.
Critical	Enact requirements for child restraint during take-off and landing	Technology is readily available. Small benefit in terms of numbers of fatalities, but large societal benefit.
High	Review lower-extremity performance requirements and practices for 16-G seating. Revise regulations (based on research) as soon as possible.	Small changes in test instrumentation and test plans could be made easily to assess potential for femur injury due to bending moments
Moderate	Review requirements for flight attendant training and recurrent training on safety issues and on safety equipment (e.g, child seats, brace positions)	Benefit is difficult to quantify because it is based on the scenario and on the individuals involved. Relatively easy to implement.
Moderate	Review procedures for training of all airport and emergency response personnel	Improved triage and emergency response procedures and training can improve moderately improve survivability
	Long Term Accomplishment	
Critical	Develop and implement new regulations to support recommended research findings	To efficiently improve passenger safety, the cycle time from safety technology development to full implementation should be reduced
High	Increase required occupant restraint to include improved torso and pelvic restraint	Benefit from improved occupant restraint relies upon improvements in the structural integrity of the aircraft, the floor, and the seats. High potential benefit when tie-down chain remains intact. Potentially costly to retrofit.
Moderate	Develop requirements for alternative methods of carry-on baggage storage	Potentially large benefit. Requires cultural change for airlines and the travelling public.

Table 4C. Recommended Investigation and Other Activities		
Subjective Assessment of Priority	**Investigation Activities**	**Comments**
High	As part of post-crash analysis, include qualified individuals from industry so that relative effectiveness of safety improvements can be determined quickly	One method to decrease cycle time for safety improvements and to create novel solutions to existing and future problems in crash safety is to involve researchers and developers more closely in the accident evaluation
High	Increase resources for accident investigation and increase focus on cause of injury, not just cause of the accident	Sufficient data for analysis must be available quickly for changes and recommendations to be implemented within a reasonable time period
Moderate	Include autopsy data in all final accident reports	Easy to implement as data is often collected. Aids determination of injury mechanisms and thereby aids development of safety technologies.
Moderate	Require data recorders capable of capturing crash loading	Technology is available. Aids determination of crash loads and comparative evaluation of safety system performance between accidents.
	Other Activities	
Moderate	Continue efforts to increase passenger awareness of safety issues	Passenger awareness and ability to react in an emergency situation increases their chance for survival

on passengers' ability to egress was disturbing, particularly since the combination of forward and downward accelerations, while severe, was not uncommon. To ensure the effectiveness of 16-G seating, it is critical to resolve this issue.

A high-priority near-term Research Activity is the application of automotive child seating technologies to aircraft seating to protect children on board aircraft. While the number of children who fly is relatively small, the societal benefit from protecting a child is large. Minor changes in aircraft seat design could be made relatively easily to take full advantage of the new child restraint systems required for automotive child seating. These technologies provide a positive attachment between the child seat and the supporting structure, eliminating this mode of potential child seat misuse.

A second high-priority Research Activity is an investigation of increasing seat back height, thus increasing passenger head protection. Additionally, other methods for improved compartmentalization of passengers should be investigated. These improvements may be relatively inexpensive to implement on new aircraft seats, but the operational issues that might arise from higher seat backs need to be evaluated.

Continued research on occupant brace position is the final recommended near-term Research Activity. While the moderate benefit of taking a fully bent-over braced position is clear, in many accidents there is insufficient warning of a crash for occupants to be instructed to take a braced position. Research issues include most appropriate foot placement and appropriate positions for small seat pitches or large occupants. The implementation costs associated with improving brace positions are low.

6.5.2 Long-Term Research Activities

Recommended critical long-term Research Activities focus on improving aircraft fuselage and floor structural integrity. Research in these areas could determine the efficacy of increasing fuselage structural integrity, controlling the break-up of the fuselage to delethalize breakage areas, and increasing the floor strength. Research challenges would be to improve aircraft structural design while minimizing added weight and complexity. The potential benefits from these activities are the largest in this study. Not surprisingly, these technologies may also be the hardest to implement. Retrofit schemes are likely to be cost-prohibitive. Fortunately, the cost of implementing improved aircraft structure in new aircraft designs may be low, as analytical and design tools are available to aid in the process.

High-priority long-term Research Activities focus on fire and smoke prevention, including fire suppression, crashworthy fuel systems, and improved materials. The activities listed here are not all-inclusive of the approaches that might be taken to mitigate the effects of fire on occupant survivability. They are merely a "snapshot" of the types of activities that could be highly beneficial to preventing fatality from smoke and fire. None of the recommended development activities are easy to achieve, nor are they easy to retrofit. However, since fire can lead to massive fatalities, activities to investigate the means for fire prevention and suppression must continue. Operational issues have a smaller potential for positive impact, but since they can be more readily implemented, they should also be considered. Issues such as the size, use, and distribution of planned exits should be investigated. Current approaches to fire suppression and planned egress may help to decrease the hazards due to on-board fires, but continued efforts are needed to reduce the number of fatalities from post-crash fires.

6.5.3 Near-Term Regulatory Activities

Three critical near-term regulatory activities were identified. These are the enactment of the 16-G seat retrofit rule, dynamic performance requirements for overhead bins, and requirements for the restraint of children during take-off and landing. Enactment of the 16-G retrofit rule can occur with existing technologies, and will provide great benefit for fatality reduction in partially survivable accidents. Only moderate additional benefit is likely to be gained by requiring human-tolerance criteria to be met with these seats; however, any changes required to meet human-tolerance criteria are most cost-effective if they are implemented as the 9-G seats are changed out.

The benefit from dynamic performance requirements for overhead bins is hard to quantify, since data from the case studies were not clear in this area. However, it was evident that overhead bins did become detached even in moderate accidents, and that overhead bins are capable of producing serious and fatal injuries. Additionally, this recommendation is particularly critical given the current state of passenger baggage. More rigid and presumably heavier bags are being carried on and stored above passengers' heads. The remediation technology required is easy to envision. Energy-absorbing devices common for other applications could be combined with strengthened bins to provide the needed solution. While these changes are easy to add to new aircraft, this solution may be somewhat costly to retrofit unless bin changes are timed with interior refurbishment.

The third critical near-term Regulatory item is the enactment of requirements for child restraint during take-off and landing. While fatalities due to lack of child restraint are not high in number, the societal benefit of protecting children is substantial. At the time of this report, this action is under FAA review.

A high-priority near-term Regulatory Activity is the review of current lower-extremity performance requirements for 16-G aircraft seating. Even before research is conducted to verify injury mechanisms (as recommended above) the current test procedures could be evaluated for measuring and evaluating femur bending moments in the vertical test condition. The use of a six-axis femur load cell in vertical seat testing instead of the current single-axis load cell used in horizontal testing may be sufficient to capture injury risk from one of the lower-extremity injury mechanisms in the Kegworth accident. An evaluation of this regulatory change could have large benefits in preventing future lower-extremity injuries due to mechanisms that will surface when 16-G seats are more fully implemented.

Moderate-priority Regulatory issues involve the review of training requirements for all personnel involved in air travel and emergency rescue. While the benefits are difficult to quantify, areas for possible improvement include training for evacuation and triage of injured passengers and more frequent review of emergency procedures. Requirements for aircraft exterior design may also be modified so that all potential exit doors or passenger egress and extrication routes are easily identified. As lives can be saved with well-executed emergency operations, further review of these issues is warranted.

6.5.4 Long-Term Regulatory Activities

The only critical long-term Regulatory Activity identified was the enactment of regulations to support the Research and Development Activities listed above. To continue to improve aircraft safety, research findings and improved technologies need to be implemented. A Regulatory action is often required before implementation will occur.

A high-priority long-term Research Activity is the increase of occupant restraint requirements to include improved torso and pelvic restraint. The technologies to accomplish this task are readily available and the benefit could be large. However, any immediate benefits will be limited by implementation of 16-G seating systems and improved floor and aircraft structure. Additionally, these restraint systems may be relatively easy to implement with new seat designs, but could be very costly to retrofit as seat structures may require changes to incorporate these technologies. While this is a high-priority item, it will take time before these technologies will show effectiveness in reducing fatalities. While these systems are commonly used in other modes of transportation, it has been generally assumed that the flying population will not readily accept three-point and other restraint systems. A regulatory driver may need to be established to overcome these pre-conceptions.

The one moderate-priority, long-term Regulatory recommendation could be more of an operational choice by the airlines rather than a Regulatory issue. There is a potentially large benefit from developing alternative methods to store baggage. Other modes of transportation provide potential schemes for baggage storage such as all under-seat storage or storage of bags by passengers in designated holding areas. However, this would require a distinct cultural and behavioral shift on the part of the airlines and the flying public to affect this change, giving it only a moderate chance of success.

6.5.5 Accident Investigation and Other Activities

Activities to improve accident investigation will not lead directly to decreased fatality in accidents. However, accurate measurement and evaluation of the field performance of safety technology are a necessary part of product improvement. Two high-priority activities in this area involve accident investigation resources. By increasing the number of NTSB staff involved in researching human factors in accidents and by allowing qualified individuals outside of the NTSB to participate directly in the human survivability portions of accident reviews, the evaluation of safety technologies could be vastly improved. Researchers who are currently actively involved in the development of safety technologies should be allowed some level of access to accident or reconstruction sites while the seats, bins, and sections of aircraft interior are available for viewing. Detailed photographs of accident scenes, combined with access to aircraft sections, would allow for faster innovation and implementation of safety improvements.

Moderate-priority Investigation Activities include the use of data recorders capable of capturing crash accelerations, the inclusion of autopsy reports and detailed medical information in all final accident reports, and requiring all interior structures to be clearly labeled with their position in the aircraft. While these are not "necessary" improvements, small changes such as these that reduce the time taken to perform post-crash analyses will increase the productivity of the limited number of individuals currently performing these tasks.

Finally, efforts to increase passenger awareness of safety issues are the responsibility of all parties involved. Although the level of passenger awareness of safety was impossible to assess in the case studies, those individuals on board the aircraft who were frequent travelers or who had military or commercial flight-related experience seemed to fare better than those seated near them in accidents and/or were also the ones who provided assistance to other passengers. Increased awareness of turbulence, brace positions, egress requirements, and child restraint could provide minor increases in occupant survivability for a very low cost.

6.6 RECOMMENDATION SUMMARY

Anticipated future air travel changes only serve to reinforce the recommendations made above and the need for actions focused on aircraft crashworthiness and occupant protection. Fleet changes are likely to include an increased number of "stretched" aircraft that will have a longer distance between planned exits and more people using those exits. The effect of these configurations should be evaluated and exits re-designed or distributed differently along the aircraft. Aging aircraft and increased demands on aircraft and airport operations could also lead to an increased number of accidents. The number of fatalities in a given accident will increase as aircraft passenger load factors increase. Finally, as the population ages and as more families with children fly, fatalities could increase in accidents involving fire due to the decreased mobility of the occupants.

The recommended activities are based on the technology needs determined through the case studies. While Simula has tried to be complete in its evaluation, there are undoubtedly other activities available to meet the same technology needs, and additional activities that may contribute to improvements in aircraft safety. If the goals established by the Gore Commission are to be met, and if they are to be accepted by the flying public, safety must increase both by avoiding accidents and by making accidents more survivable. During the time period of this database review, there were almost as many partially survivable accidents as there were non-survivable accidents. When seeking to decrease the rate of accidents that result in fatalities, increasing crashworthiness and avoiding accidents altogether might have similar effects on reducing fatalities. This report has provided a description of a number of potential technologies and activities that can both increase the range of survivable accidents and can decrease the number of fatalities in partially survivable accidents.

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