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Recommendations for Injury Prevention in Transport Aviation Accidents

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ABSTRACT

In 1996, a national objective was established to reduce the rate of fatal accidents in aviation. To assist in determining the best methods for improving aircraft crash survivability, a combined approach was used involving database research and the examination of case studies of transport aviation accidents. The results of the study include recommendations for maintaining occupiable space, enhancing occupant restraint, managing energy transferred to the occupant, improving egress, and increasing post-crash survival.

INTRODUCTION

In 1996, the Gore Commission established a 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 to 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. Maintaining an occupiable volume is the first step in providing occupant protection.
2. **Occupant Restraint** - The occupant must be restrained within the occupiable 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 for initial survival and for allowing a passenger to affect their own egress. Injurious interaction with interior strike hazards should be minimized. These 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.). Energy transferred to the occupant can be managed through such systems as energy-absorbing seats, improved restraint systems, and delethalized interiors.
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 objective of this program was to identify and prioritize the technologies or development efforts that will provide the largest effect for reducing fatalities in transport aircraft.

BACKGROUND

Previous studies of transport-category aircraft accidents have led researchers to make a number of recommendations to improve aircraft safety. There have been a number of accidents over the years involving serious injuries and fatalities attributed to seat-to-floor connection failures, the lack of energy absorption in seating, and delethalization of seat backs. (References 1, 2, 3, and 4). 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 (References 5 and 6). One of the most prominent safety concerns in transport aircraft over the years has been in preventing deaths due to smoke inhalation and fire. Advancements in making seat upholstery and the cabin interior more fire retardant, and safety aids such as smoke hoods and emergency lighting have been investigated throughout the years as egress-assisting devices (e.g., Reference 7). Because of the complexity and relative uniqueness of transport aircraft accidents, prioritizing among the available improvements is a difficult challenge.

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 detailed case studies allowed consideration of specific safety technologies that 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. Results from the database evaluation can be found in the full report (Reference 8).

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 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. The level of detail in the case reports was the limiting factor in the level of detail in the investigation. For the most part, Simula was limited to the data presented in the publicly available NTSB final reports.

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

A team of medical and accident reconstruction experts was gathered to review the case studies. 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 occupants' needs that went unmet by the available technologies were determined. 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.

CASE STUDY RESULTS AND ANALYSIS

Since the purpose of this study is to identify various 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.

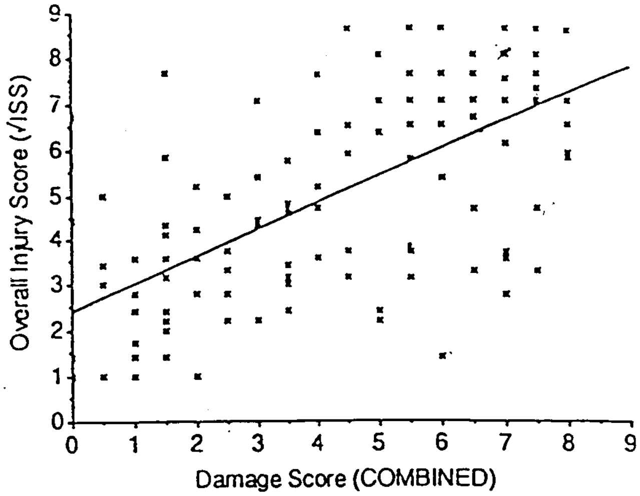
MAINTAINING OCCUPIABLE SPACE

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.

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.

In a detailed study of the 1989 Kegworth accident, White, et al., correlated the structural damage to the severity of injury (Reference 9). 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 1). 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.



√ISS vs. combined damage score.

Figure 1.
Positive correlation between aircraft and seat damage and Injury Severity Score in the 1989 Kegworth accident (Reference 9).

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 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.

Recommendations

Structural damage to the aircraft, through crushing or through the aircraft breaking up on impact, can lead to the loss of the occupant's occupiable volume. 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 for retrofit applications.

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. A long-term solution to improving occupant survivability, both for occupiable volume and to assist in egress, is to construct the aircraft fuselage with break points that 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 have the highest tendency 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.

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. The following discussion focuses on the tie-down chain with 9-G and 16-G seats considered separately.

9-G Seats

Where 9-G seats were used, seat failure and seat tear-out from the floor was more evident. In all of the case studies, except for the 1991 Los Angeles accident, the -G seats 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 nine 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.

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 (Reference 10). Consequently, these new seats should have been able to stay in the floor tracks much better than previous seat designs.

Figure 2 shows the injury breakdown 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. 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.

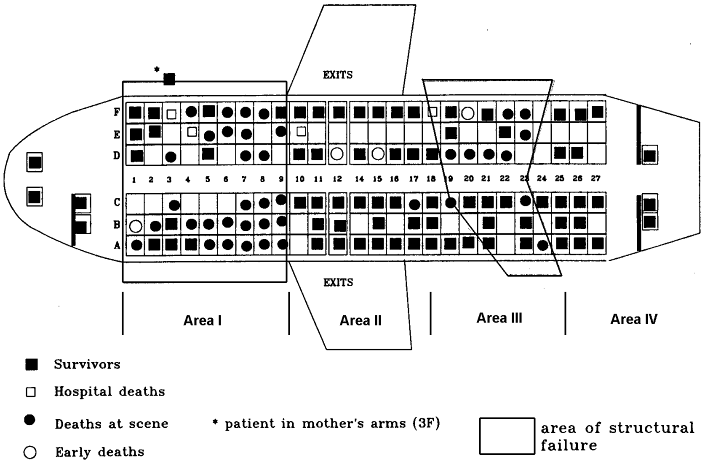


Figure 2.
Breakdown of injury severity (Reference 11)

Area I was crushed and floor integrity was lost. All of the floor beams failed in this area, causing 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. Seat damage indicated that loading in this area was likely greater than 16 G, and was probably closer to 20 G. The majority of occupants in this section, particularly those near the rear break in the section, were fatally injured, most suffering multiple extreme blunt trauma injuries. It is clear that an increase in the crashworthiness of the floor structure is a prerequisite for other increases in survivability 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 same 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. Based on seat deformation, it could be determined that loads transferred to the seats in this section were at least as high as the loads in Area I. However, since the floor structure and the seats remained relatively intact, survivability was high. There were only four fatalities in this area, two of which were attributed to posterior head impact from an overhead luggage bin (Reference 9). 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 the 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. Seat deformation indicated lower seat loading than in other sections. Of the seats 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 subsequently less 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. The tail section experienced a less-severe scenario than did the more forward sections with less structural deformation. This is not surprising, since the aircraft impacted on an upward slope with the crushing of forward sections absorbing 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 and deformation of the seats. 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.

Recommendations

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. 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 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 limit that motion and reduce the number of seats that are torn out during the impact event.

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 12). 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 occupant's 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 occupant. Many “front-row” seat designs with alternative restraint systems have been developed, but have not been fully implemented. To implement three-point restraints, the seats' structural designs would likely have to be changed, making retrofit of these systems costly.

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 or when the injury level prevents effective egress. 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 head and lower extremity injury related to seats, the overhead bins, and the use of the brace position to help manage occupant vulnerability to injury.

Head Injury

The Head Injury Criteria, or HIC, is commonly used as a measure of head injury potential in other modes of transportation (particularly in the automotive industry). 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 13). The application of this standard to new seating systems is relevant, based on the case study results that indicate head contact occurring with the row of seats in front of the occupant. However, the HIC criterion was not designed to measure 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 14).

Recommendations

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 maximum of a 36-msec time interval, in a manner consistent with the automotive industry (Reference 15). 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 improved head injury protection in the future.

The second recommendation is that the FAA and other interested parties fund research into the measurement of unconsciousness. 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.

The third recommendation is to include head injury evaluation into a 16-G seat retrofit ruling. 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.

Injury to the Lower Extremities

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. 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.

Recommendations

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 16). An accepted practice 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. Updates in test manikin technology (e.g., Reference 17) make it possible for the types of injury mechanisms seen in these accidents to be evaluated. Consequently, the test standard should be updated, and a review of other potential injury mechanisms and associated test procedures should be conducted.

To increase survivability rates, more must be done than simply exchanging one mechanism of serious injury for another one. While passengers with severe lower-extremity injuries survived the Kegworth accident, they might not have if immediate egress had been required. In association with reviewing the use of additional lower-extremity injury performance measures, further research is recommended into the femur bending mechanisms identified with the 16-G seats so that these mechanisms can be understood and seat designs can be modified to prevent loss of life under similar future circumstances.

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 14). For occupants over the wingbox, posterior head injury was noted even when seat damage was minimal. Although there are only a handful of cases where impact from the overhead bin may have directly caused a 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, hindrance from egress and 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 otherwise had very 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.

Recommendations

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, discussed in the next section, that might help reduce the risk of head and upper torso injury is to increase the seat back height to enhance the "protective shell" around the occupant.

Seat Back Height

In three of the 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.

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 explanation for her survival is that her short stature and the presence those seated around her shielded her from fatal injury.

Recommendations:

Since 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. This solution is inexpensive and could be easily implemented on new seats.

Crash Brace Position

One method currently utilized to manage the loads transferred to occupants 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 a forward strike hazard. In the case studies, there is substantial evidence of head and face strikes with the row of seats in front of them when occupants were not braced.

The NTSB report from the 1990 Cove Neck accident reports that passengers were not given warning of the crash, and that passengers were not instructed to take a brace position (Reference 18). 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 14), 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 detailed instructions about the appropriate position to adopt. Variations in lower-extremity injury in this accident could also be attributed to variations in pre-crash position.

In an internal Simula investigation, the sequences of aircraft accidents (Part 121, 129 and 135) were evaluated to determine if there was sufficient time available for crew to instruct occupants to take a crash brace position (Reference 19). 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.

Recommendations

Simula recommends that additional efforts be made to determine the best position for bracing and the best methods for educating and communicating with 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.

EGRESS AND ENVIRONMENT

The final critical element to surviving an aircraft accident is the occupant's 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.

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 that 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 nine passengers died from smoke inhalation behind a door that they could not open, and the 1990 Cove Neck accident in which at least two 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, from contact with hot or sharp-edged metal, and dangers from an assortment of items including wiring harnesses and jet fuel.

Recommendations:

Survival should rely upon planned methods of egress instead of upon chance. 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.

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 1988 Dallas/Fort Worth accident was caused by improper configuration on take-off. Passengers had no warning of the accident, but the crash was relatively mild. The nine passengers who died from smoke inhalation were found around the rear door of the aircraft, apparently unable to open the exit before being rendered unconscious by smoke. 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, a Boeing 737 collided during landing with a Metro II commuter aircraft holding on the runway. Of the 6 crew and 83 passengers aboard the 737, 19 passengers and 1 flight attendant were fatally injured due to smoke inhalation. A fire broke out before the aircraft came to 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. The exit door was placed on the seat in the exit row and a seat back pushed over the door partially blocking the exit, further hampered egress. 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. On the positive side, the floor track lighting was effective in leading some passengers to a useable rear exit

Recommendations

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 20).

One technology that is commercially available for extending the time to egress is the smoke hood. Presumably a passenger could don a 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. 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.

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 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 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.

Recommendations

In April of 1998, the FAA sought public comment on an advanced notice of proposed rulemaking on this topic (Reference 21). Despite numerous recommendations for the restraint of children under 2 (e.g., References 22 and 23), regulatory action has not been forthcoming. Unfortunately, even if children are required to be restrained, the level of safety provided by even “FAA-approved” seats may be not be adequate (Reference 24). Additional changes in automotive safety seats may increase incompatibility issues between automotive and aviation applications. Immediate action should be taken to require appropriate restraint for all children on aircraft. Appropriate restraint entails both the restraint of children under the age of 2 in their own child safety seat and appropriate regulations and design standards so that child safety seats, for children through age 4 or 40 lbs., provide appropriate aviation-specific protection. All efforts should be made to ensure that children are provided with an equivalent level of safety as adult passengers.

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 25). Simula's database evaluation 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. While injuries to crew and passengers who were standing during the turbulence event predominate, 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.

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.

EMERGENCY RESPONSE

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.

CONCLUSIONS AND RECOMMENDATIONS

Full and effective implementation of safety improvements requires several key steps (Reference 26). 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.

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 by seat number and vital statistics (e.g., age, height, weight, etc.), then personal identities can be protected when medical data is reported.

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 in which 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. 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.

CAUSE OF INJURY SUMMARY

Table 2 summarizes the primary causes of injury in each case study. In relative order of importance, maintaining occupiable space is the most critical consideration for survival. The integrity of the tie-down chain for occupant restraint and the limitation of fire-related hazards follow. It might seem contrary to common sense that the restraint of the occupant did not factor most 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.

The danger related to fire and its effects can be masked by chance. 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. One limitation of the case study approach is that the overall hazard from fire cannot be fully assessed.

Table 2.
Summary of injury mechanisms by technology area for each accident case study

Accident Description	**Occupiable Space**	**Restraint**			**Energy Management**		**Egress**		**Child Passenger Protection**
		Floor	**Seat**	**Occupant**	**Seating**	**Baggage**	**Exits**	**Fire, Smoke, and Toxicity**	
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	**								
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									

TECHNOLOGY SUMMARY

The technologies recommended from the case study evaluations are summarized in Table 3. 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. Additionally, there are some inherent trade-offs and synergies among the technologies that have not been thoroughly evaluated. For example, the use of three-point restraints could reduce the need to delethalize seat backs, or the use of planned break-up or crush zones in the aircraft structure could limit the need for improved exit door designs.

Table 3. **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

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 options available to meet the same technology needs, and additional actions that may contribute to improvements in aircraft safety. If the goals established by the Gore Commission are to be met, 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. 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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