Human Tolerance and Crash Survivability

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ABSTRACT

Aircraft and motor vehicle crashes will continue to occur in spite of all human efforts to prevent them. However, serious injury and death are not inevitable consequences of these crashes. It has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for the occupants of these aircraft. Nevertheless, many deaths and serious injuries occur in crashes that are classified as "survivable". This is because the protective systems within the aircraft such as seats, restraint systems, and cabin strength were inadequate to protect the occupants in a crash that would have otherwise been non-injurious. In order to maximize survivability in a crash, one must have an understanding of the tolerance of humans to abrupt acceleration and then design an aircraft that is capable of maintaining its cabin/cockpit integrity up to the limits of human tolerance. This should be combined with judicious use of energy absorbing technologies that reduce accelerations experienced by the occupants and by restraint systems that provide appropriate support and prevent injurious contacts. This paper discusses basic principles of human tolerance to abrupt acceleration as well as basic concepts of crashworthiness design. Although these concepts are discussed in the context of helicopter crashes, the same principles apply to other vehicles.

INTRODUCTION

Aircraft and motor vehicle crashes will continue to occur in spite of all human efforts to prevent them. However, serious injury and death are not inevitable consequences of these crashes. It has been estimated that approximately 85 percent of all aircraft crashes are potentially survivable without serious injury for the occupants of these aircraft (1,2,3). This estimate is based upon the determination that 85 percent of all crashes met two basic criteria. First, the forces involved in the crash were within the limits of human tolerance without serious injury to abrupt acceleration (1). Second, the structure within the occupant's immediate environment remained substantially intact, providing a livable volume throughout the crash sequence (1). In other words, contrary to popular belief, most aircraft crashes are not "smoking holes".

Nevertheless, many deaths and serious injuries occur in crashes that were classified as "survivable" by crash investigators. This is because the protective systems within the aircraft such as cabin strength, seats, and restraint systems were inadequate to protect the occupants in a crash that would have otherwise been non-injurious. This is why the definition of survivability of a crash is based solely on aircraft and impact related factors and not upon the outcome for the occupants of the crashed aircraft. A mismatch between the survivability of the crash and the outcome for the occupants suggests an inadequacy of protective systems design or utilization.

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It should also be recognized that transmission of forces to the occupants as well as the degree a vehicle maintains its structural integrity during a crash, the two components of survivability, are determined, in large part, by the design of the vehicle. The process of establishing the degree to which any particular vehicle will protect occupants in a crash, or its crashworthiness, involves a series of trade-off decisions during its design and manufacture. One of the adages of aircraft design, “it is possible to build a brick outhouse, but you can’t make it fly”, applies to this situation. Increased crashworthiness and advanced crash protection systems increase both the cost and the weight of the final design and, therefore, potentially decrease profit margins as well as aircraft performance. The “trade-off” is to provide the right degree of protection for the projected crash environment without sacrificing too much in terms of cost or performance. Obviously, the bases for determining the “right” trade-off are frequently the source of considerable debate both during the design phase and over the lifetime of any vehicle. One recurring error in these trade-off decisions is a lack of understanding of human tolerance and protection concepts by the decision makers as well as a failure to adequately determine or estimate the crash environment.

The other factor entering into this process is government design requirements. These requirements are also the result of considerable compromise made more for political and economic reasons than for their technical merit. Suffice it to say that Federal design standards should be considered minimal requirements and not representative of the current state-of-the-art in occupant protection.

To fully understand these issues requires a clear comprehension of the crash environment to which any particular vehicle is exposed as well as an understanding of human tolerance to acceleration and the basic principles of occupant crash protection. The purpose of this paper is to introduce the reader to some of the more basic concepts relating to personal survival in aircraft and other vehicular crashes.

COORDINATE SYSTEMS

1. Injury in a crash is the result of human response to force application to the body. Force and acceleration are vector quantities comprising both magnitude and direction.
2. For purposes of description, both the aircraft and the seated human are arbitrarily assigned coordinate axes which are related as follows (Figures 1 and 2):

Aircraft	Human
Roll	X
Pitch	Y
Yaw	Z

3. Any applied force or acceleration may be described according to its components directed along each of the orthogonal axes.
4. Figure 1 is a representation of the aircraft coordinate system commonly used in military and other government publications and standards. It represents a “left-hand rule” coordinate system (1). It should be noted that there are other coordinate systems in use, and it is important for the reader to establish which system is in use for any particular publication or standard.

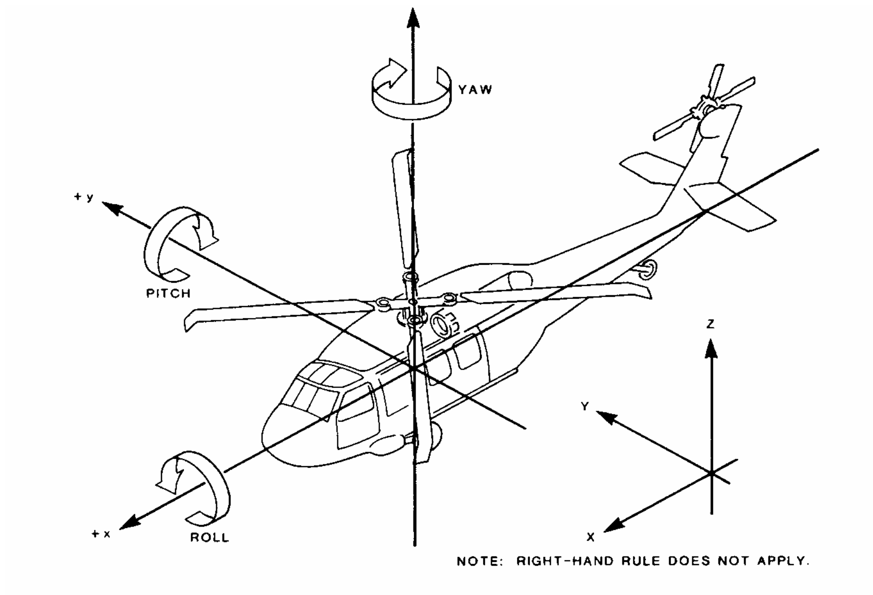

Figure 1. Aircraft coordinates

5. Figure 2 depicts a commonly used coordinate system applied to the seated human. The reference to movement of the eyeballs describes the body's inertial reaction to the applied acceleration, which is opposite and equal to the applied acceleration (1). It is the body's inertial response to an acceleration that results in injury.

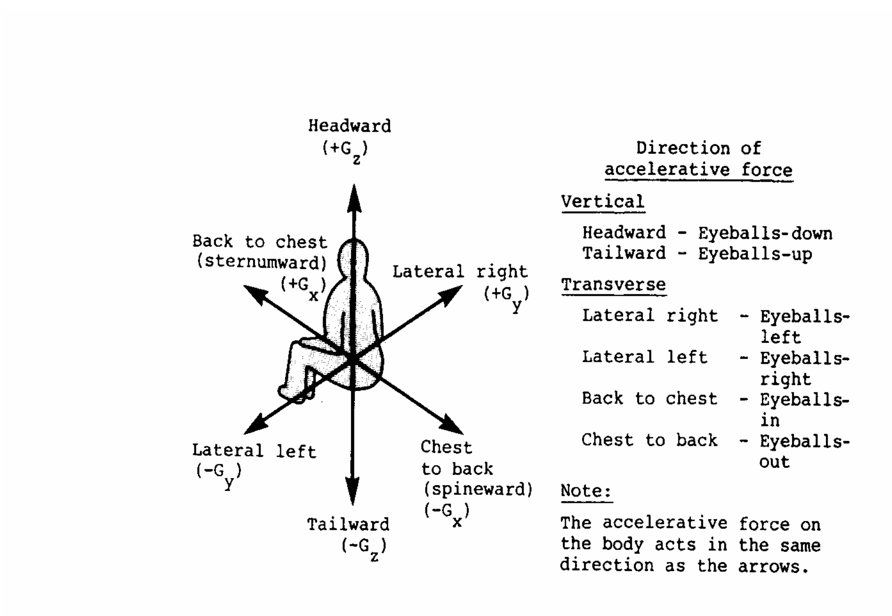

Figure 2. Human coordinate system

ACCELERATION

1. Acceleration is defined as the rate of change in velocity of a mass and is frequently stated in units of feet per second per second or feet/second^2 (meters/second^2. It is related to force by the familiar equation, F = ma, where F = force, m = mass, and a = acceleration.
2. Acceleration may be described in units of G which is the ratio of a particular acceleration (a) to the acceleration of gravity at sea level (g = 32.2 ft/sec^2 or 9.8 m/sec^2) or G = a/g. As a result, crash forces can be thought of in terms of multiples of the weight of the objects being accelerated.
3. Acceleration values given in various reports generally refer to the acceleration of the vehicle near its center of mass, unless otherwise specified.
4. Note that a deceleration is simply a negative acceleration.
5. An impact or crash is frequently described in terms of a crash pulse (Figure 3). A crash pulse is a description of the accelerations occurring in the crash over time, or the acceleration-time history of the crash. Although the shape of a crash pulse can be highly complex and variable from crash to crash, for practical purposes, most aircraft and automobile crash pulses may be considered to be generally triangular in shape. This assumption vastly simplifies calculations related to the crash and provides reasonable estimates of acceleration exposure for field investigators. Note that in a triangular pulse, the average acceleration of a pulse is one-half of the peak acceleration.

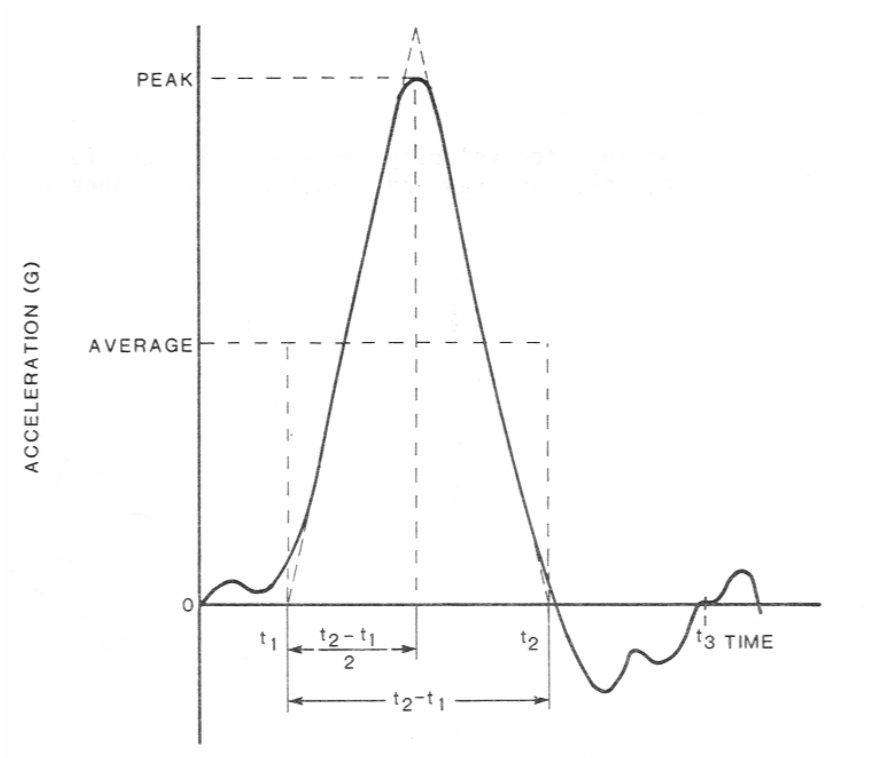

Figure 3. Triangular Crash Pulse

6. If the velocity of the vehicle at the time of the crash can be estimated and the stopping distance (vehicle crush plus soil deformation) measured then the acceleration of the vehicle during the crash can be estimated through a simple formula, assuming a triangular pulse:

a. $$\text{Peak G} = \frac{v^2}{(g) \times s}$$

where v = velocity change of the impact,
s = stopping distance and,
g = acceleration of gravity at sea level = 32.2 ft/s^2 or 9.8 m/s^2

b. Average G is equal to one half of the peak G.

TOLERANCE TO ABRUPT ACCELERATION

1. An understanding of human tolerance to abrupt acceleration is essential to developing appropriate crashworthiness or protective system design standards for any vehicle. If one knows the crash environment to which a vehicle will be exposed and the limits of human tolerance to acceleration, then one can rationally develop crashworthiness design requirements to protect occupants in foreseeable crashes of that vehicle.
2. In general, human tolerance to acceleration is a function of five extrinsic factors (5). These factors are related to characteristics of the crash pulse and to the design of the seating and restraint systems:
   a. **Magnitude** of the acceleration
      Clearly, the higher the acceleration, the more likely it is to cause injury.
   b. **Direction** of the acceleration
      The human is better able to withstand accelerations applied along certain axes of the body (Figures 4 and 6). The direction that is most tolerable is the $+G_x$ or acceleration in the forward direction (eyeballs in). The least tolerable direction is apparently the G_z or vertical axis (eyeballs up or down). The lateral axis (G_y) used to be considered the least tolerable, but recent data derived from crashes of Indianapolis Race Cars indicates that this is probably not the case.
   c. **Duration** of the acceleration
      How long one is subjected to an acceleration is one of the determinants of human tolerance. In general, the shorter the pulse for the same magnitude of acceleration, the more tolerable (Figures 4 and 6). Acceleration tolerance is usually considered to comprise two distinct realms—abrupt acceleration and sustained acceleration—because of distinctly different human response patterns to abrupt and sustained accelerations. Most crash impacts have a duration of less than 250 milliseconds or one-quarter of a second, which is considered to be in the realm of abrupt acceleration. Human tissues and the vascular system respond considerably differently to these very short duration pulses than they do the more sustained pulses experienced by fighter pilots and astronauts. Consequently, a 10 G turn or "pull-up" may cause unconsciousness in a pilot and result in a crash, but a 10 G crash impact may have little effect on the occupant of an automobile or aircraft.
   d. **Rate** of onset
      Rate of onset of acceleration refers to how rapidly the acceleration is applied. It is reflected in the slope of the curve depicted in figure 3. For a given magnitude and duration of acceleration, the greater the rate of onset, the less tolerable the acceleration (Figure 5).
   e. **Position/Restraint/Support**
      This is one of the most critical factors determining human tolerance to a crash pulse. It refers to how well the occupant is restrained and supported by his seat and restraint system and the degree to which the loads experienced in the crash are distributed over his body surface. It is this factor

that is the primary determinant of lack of survival in a survivable crash, if post-crash fire is excluded.

3. Also of importance in considering human tolerance to abrupt acceleration are various intrinsic factors, or factors that are directly related to the individual subjected to the impact. These factors are independent of the extrinsic factors discussed above. They, in large part, explain the observed biological variability of humans subjected to identical impacts:
   a. **Age** of the subject
      Young, healthy adults are best able to withstand impact accelerations. Consequently, a vehicle designed for military applications may allow more severe accelerations to be experienced by occupants than a vehicle intended for the general population.
   b. **Health** of subject
      Chronic medical conditions such as heart disease and osteoporosis, clearly degrade one's ability to withstand impact accelerations. History of previous injuries may also adversely affect one's tolerance.
   c. **Sex** of subject
      There are clearly sex differences in tolerance to acceleration. Women have a different mass distribution than men as well as differences in muscle mass. This has been of particular concern for the neck where women have approximately one third less muscle mass than men of comparable stature.
   d. **Physical conditioning**
      Physical conditioning appears to increase ones tolerance both to abrupt and sustained acceleration, probably due to increases in muscle mass and strength. Physical conditioning is also considered to be a factor in recovery from injuries.
   e. **Other** factors
      Certainly, there are other intrinsic factors that affect one's ability to withstand acceleration. Unfortunately, these various factors will probably remain somewhat nebulous due to the obvious limitations on performing research in this area.

HUMAN TOLERANCE CURVES (EIBAND CURVES)

1. In 1959, Eiband compiled what was then known about the tolerance of a restrained individual to abrupt accelerations (1). These data were compiled primarily from the pioneering work of Colonel John Stapp who performed human tolerance experiments on live volunteers, himself and coworkers, using acceleration sleds and other acceleration devices. Eiband also included in his summary, human surrogate experiments that had also been performed. The tolerance curves that Eiband constructed are illustrated below in Figures 4 and 6.
2. Figure 4 is the Eiband Curve for accelerations in the $+G_z$ axis, analogous to the direction of forces experienced in an ejection seat or a vertical crash of a helicopter. It is a plot of uniform acceleration of the vehicle as demonstrated in the lower right-hand corner, versus the duration of the acceleration for pulses up to approximately 150 milliseconds. As the legend on the graphs notes, these exposures were all survivable with essentially idealized seat and restraint systems. The graph illustrates that individuals voluntarily tolerate accelerations up to approximately 18 G without injury, and spinal injury does not occur below accelerations of approximately 20-25 G.
3. Figure 6 depicts the analogous curve for the $-G_x$ direction, such as would be experienced in a head-on collision. Note that the tolerance in this axis is over 40 G.
4. Similar curves are available for the other axes. A summary of estimates of human tolerance in all axes is shown below:

Human Tolerance Limits

Direction of Accelerative Force	Occupant's Inertial Response	Tolerance Level
Headward (+ Gz)	Eyeballs Down	20-25 G
Tailward (- Gz)	Eyeballs Up	15 G
Lateral Right (+ Gy)	Eyeballs Left	20 G
Lateral Left (- Gy)	Eyeballs Right	20 G
Back to Chest (+Gx)	Eyeballs Out	45 G
Chest to Back (- Gx)	Eyeballs In	45 G

Note: Reference: Crash Survival Design Guide, TR 79-22.
(0.10 Second time duration of crash pulse; full restraint)

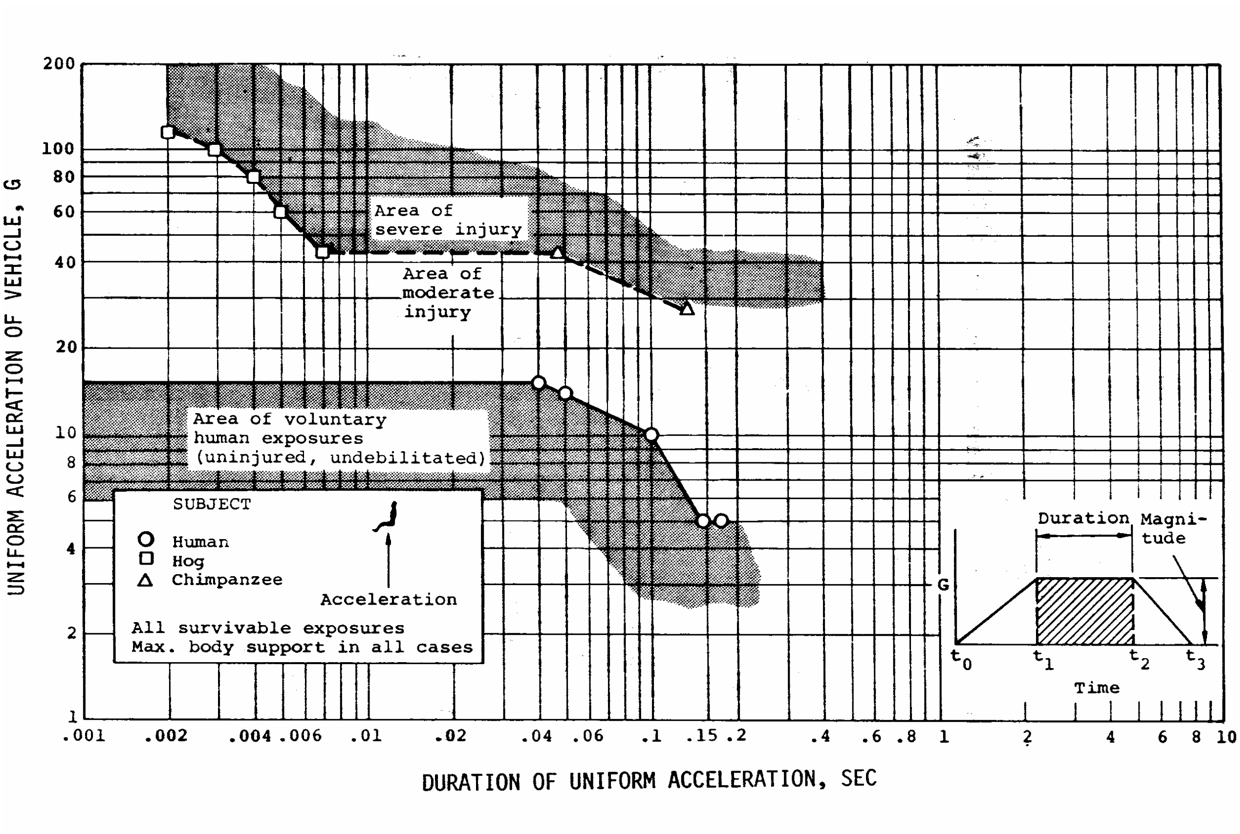

Figure 4. Eiband Curve for $+G_z$

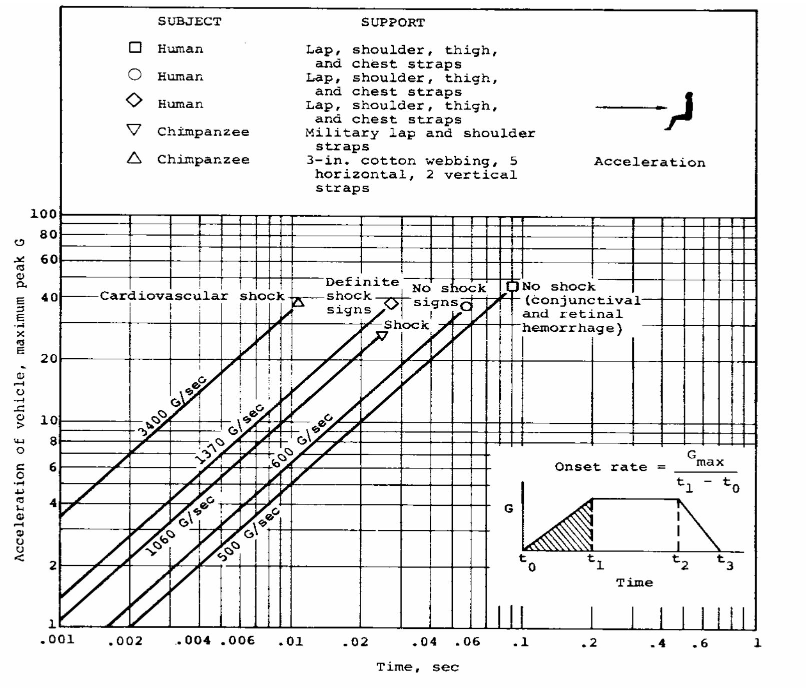

Figure 5. Effect of Rate of Onset

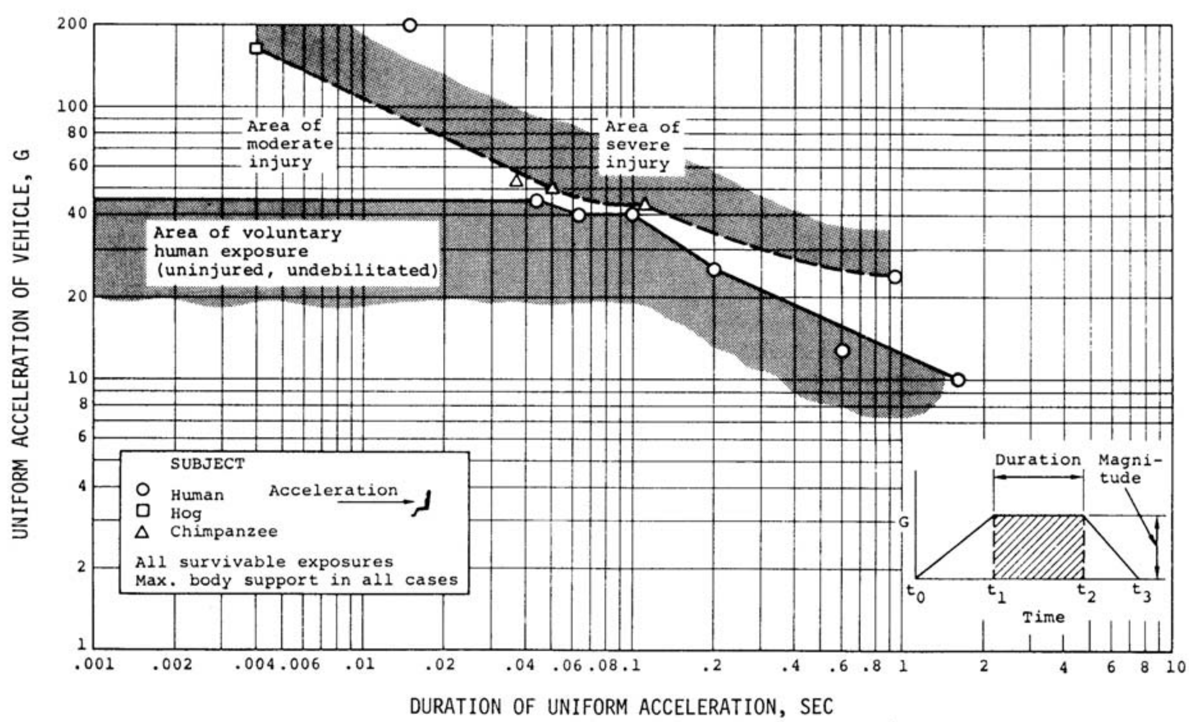

Figure 6. Eiband Curve for $-G_x$

CLASSIFICATION OF TRAUMATIC INJURY

1. At the risk of oversimplifying the issue, it is useful from a designer's or investigator's standpoint to divide injury suffered in vehicular crashes into **mechanical injury** and **environmental injury**. Mechanical injury is further subdivided into **contact injury** and **acceleration injury** (4). Environmental injury refers to burns, both chemical and thermal, and events such as drowning.
2. In a strict sense both acceleration and contact injuries arise from application of force to the body through an area of contact with an accelerating surface. In the case of acceleration injury, the application is more distributed so that the site of force application usually does not receive a significant injury. The site of injury is distant from the area of application and is due to the body's inertial response to the acceleration. An example of acceleration injury is rupture of the aorta in a high sink rate crash. Here the application of force occurs through the individual's thighs, buttocks, and back where he is in contact with the seat. The injury itself is due to shearing forces at the aorta generated from the inertial response of the heart and aorta to the upward acceleration of the body.
3. A contact injury occurs when a localized portion of the body comes into contact with a surface in such a manner that injury occurs at the site of the contact ("the secondary collision"). Relative motion between the body part and the contacting surface is required. An example of this type of injury is a depressed skull fracture resulting from the head striking a bulkhead.
4. A mixed form of injury may also occur when acceleration generated by a localized contact produces injury at a site distant from the point of contact as well as at the point of contact. An example of this type of injury is a contracoup brain injury.
5. Distinction is made between these two basic forms of injury since prevention involves different strategies. Providing means of absorbing the energy of a crash before it can be transmitted to an occupant prevents acceleration injury. Structural crush zones, energy absorbing seats, and energy absorbing landing gear all provide this function.
6. The primary strategy employed to prevent contact injury, on the other hand, is to prevent the contact between the occupant and a potentially injurious object. This can be accomplished through a variety of methods including improved occupant restraint or relocation of the potentially injurious object. If contact cannot be prevented, injury can be mitigated by reducing the consequences of body contact through such strategies as padding of the object, or making the object frangible so that contact causes the object to yield before injury occurs.

RESTRAINT ISSUES

1. As discussed above, good restraint is critical to survival in all but the most minor impacts. Restraint systems serve many important functions including:
   a. Preventing ejection of occupants from their seats or the vehicle
   b. Preventing the "secondary collision" which refers to body impact with interior structures in the vehicle such as windshields, controls, and instrument panels due to flailing of the body in response to accelerations caused by the vehicle collision.
   c. Distributing crash loads over a wide portion of the body. This is essential in frontal impacts for forward facing occupants. Properly designed restraints also ensure these loads are borne by the portions of the body most able to withstand dynamic forces namely the pelvis, chest, and shoulder girdle. Restraints that contact the neck or ride up into the abdomen can result in dire consequences for the occupant in relatively minor impacts.
   d. Tightly coupling the body to the vehicle, thus preventing magnification of forces due the development of relative velocities between the decelerating vehicle and its occupants (dynamic overshoot).
   e. Providing for "ride down" of the crash forces.

2. Prevention of the secondary collision is essential to crash survival since relatively minor crashes can result in fatal impacts with interior vehicle structures. There are many different types of belt restraint systems available today, but they mainly involve either pelvic restraint (lap belt) or upper torso restraint (shoulder belt) or a combination of both (3-point, 4-point, and 5-point systems).
3. Lap belt only configurations (2-point restraints) permit tremendous flail of the upper torso in crashes as shown in Figure 6. The upper torso flail illustrated in this figure is for a 95th percentile male Army aviator subjected to a 30 G forward and 30 G lateral impact on an acceleration sled (1). The amount of excursion depicted is the average of a number of tests. With a head excursion of approximately 40 inches (102 cm.) in the forward direction, it can be seen why lap belt only restraint will not protect a driver of a car or pilot of an aircraft from impact with control surfaces or the instrument panel.
4. Figure 7 illustrates how these strike envelopes are significantly reduced for the same impact conditions when dual harness upper torso restraint and tie-down strap is added to the system (5-point restraint).
5. An Additional advantage offered by upper torso restraint in combination with pelvic restraint is that multi-belt restraints provide additional distribution of impact loads across the upper torso instead of focusing the entire load across a 2 to 3 inch strip across the pelvis.
6. Upper torso restraint and tie-down straps also help prevent a situation known as "submarining" from occurring (Figure 7). This is where the lap belt rides over the pelvic brim and compresses the soft tissues of the abdomen resulting in serious abdominal and spinal injuries. Submarining occurs due to the pelvis rotating under the lap belt, usually due to inappropriate location of the lap belt anchors or due to poor design of the seat bottom or a combination of both. Lap belt only restraints so commonly inflicted serious injuries on users in automobile crashes that the medical community coined a new term, "the seat belt syndrome", to describe the constellation of injuries caused by submarining under the lap belt (6, 9, 10).
7. An exciting new development in helicopter restraint systems is the planned implementation of inflatable restraint systems in Army helicopters. These systems include air bag systems similar to those used in automobiles as well as inflatable bags contained in belt restraint systems intended to provide pretensioning and body support. Such systems are projected to reduce injury in crashes of some helicopters by as much as 30 percent.

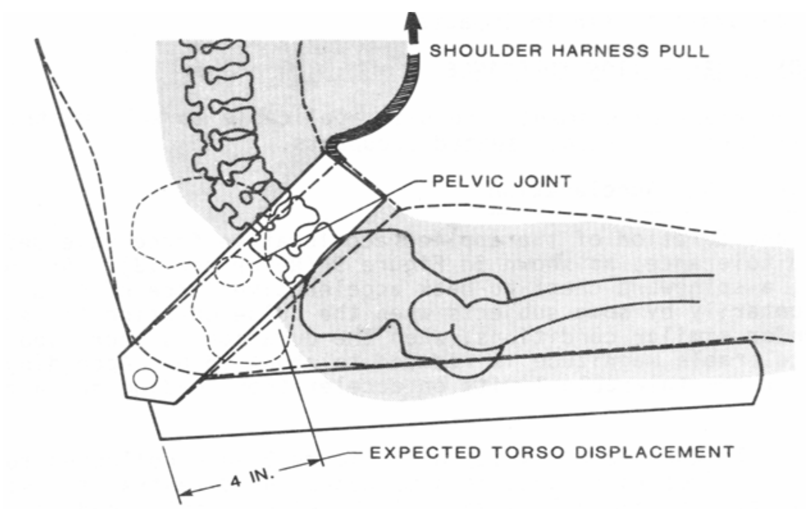

Figure 7. Submarining

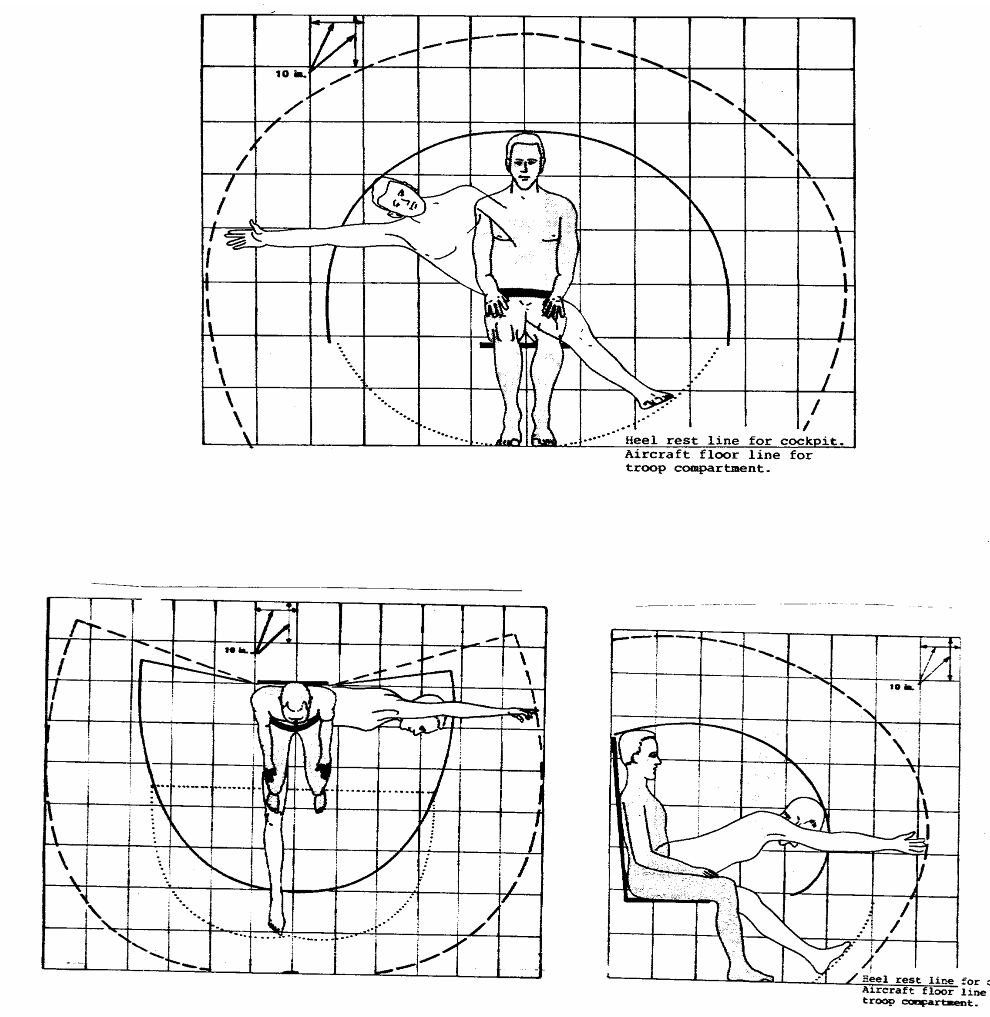

Figure 8. Strike Envelope for Lap Belt Restraint

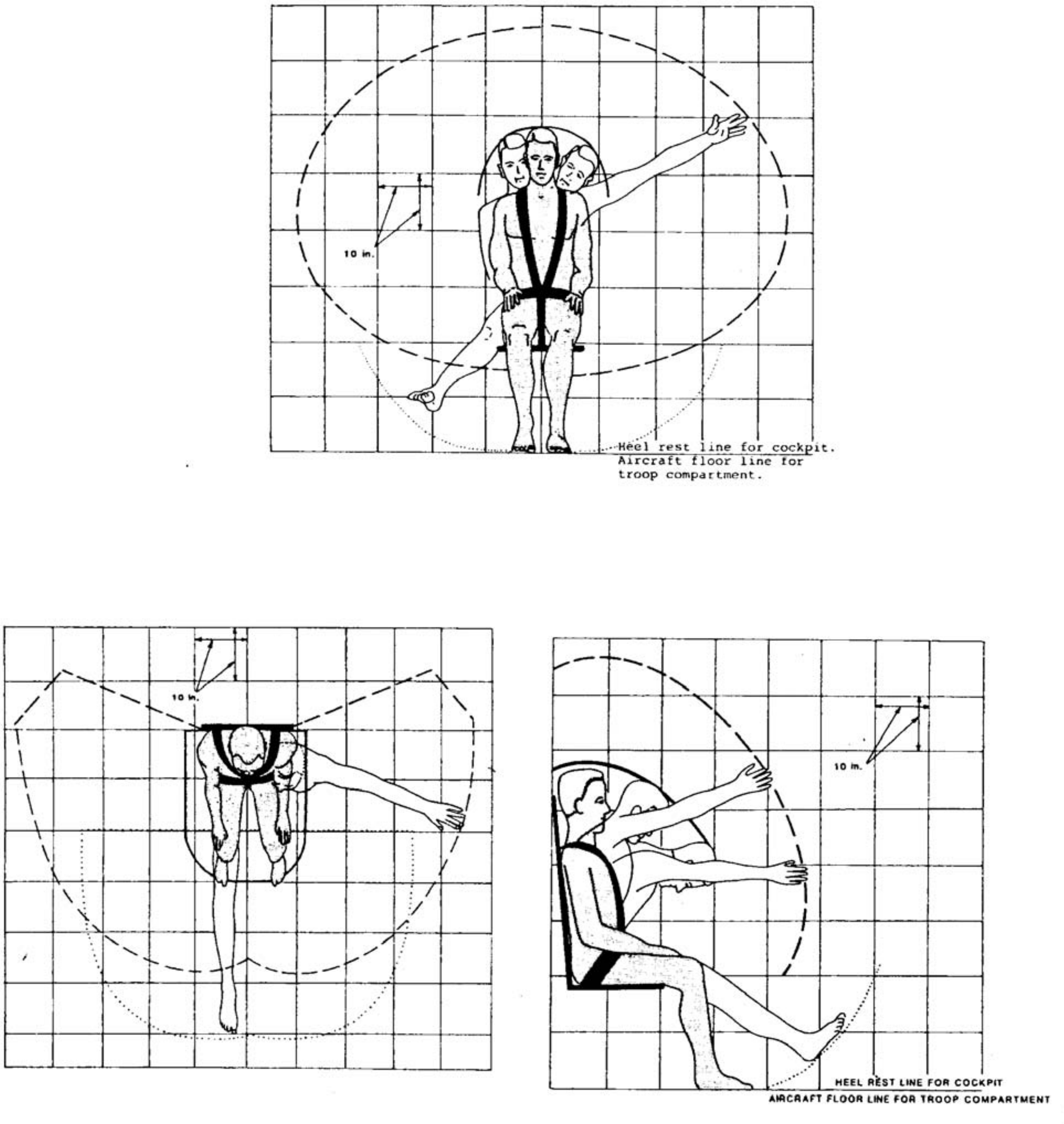

Figure 9. Strike Envelope for 5-Point Restraint.

PERSONAL SURVIVAL IN VEHICULAR CRASHES

1. The above discussion was directed toward human tolerance to impact for relatively ideally restrained occupants subjected to abrupt accelerations. In practice, occupants are rarely ideally restrained and there are many other factors beside restraint and acceleration involved in the crash, which determine whether a person is injured, or not.
2. In analyzing personal outcome for individuals involved in a particular crash, many investigators use what is known as the "CREEP Principle". CREEP is merely an acronym for the five factors considered to influence personal survival in a crash. Although these factors may not encompass the entire complex set of factors involved in surviving a crash, they provide an extremely useful framework for conducting a systematic analysis (5) of personal survival. The five factors are:
    a. **C**ontainer

       The potential for survival during a crash is severely compromised if the occupied spaces collapse or are penetrated by external objects.
    b. **R**estraint

       Effective personal restraint is essential for injury prevention in all but the most minor crashes. Of almost equal importance is restraint of potentially injurious objects within the cabin space such as cargo and luggage.
    c. **E**nvironment

       This refers to potentially injurious objects located within the strike zone of each occupant. Ideally restraints systems should prevent occupant contact with internal structures. If the strike cannot be prevented in foreseeable crashes, then the object should be relocated, or if this is not feasible, it should be rendered non-injurious by padding or frangibility.
    d. **E**nergy Absorption

       In severe crashes, accelerations may exceed human tolerance limits in spite of excellent restraint and seat systems. Under these circumstances, providing means of managing the energy of the crash in a controlled manner can greatly increase the survivability envelope. Automobile designers accomplish this by providing "crush zones" in the front and rear of automobiles wherein crushing of the vehicle structure absorbs a portion of the energy of the crash, thus reducing the forces experienced by the occupants. Helicopters tend to crash mainly in a vertical direction creating very high accelerations in the vertical axis. Rather than increasing structure in the bottom of helicopters to help absorb energy in these crashes, many military helicopters are provided with energy absorbing seats. These seats stroke vertically in a crash, thus absorbing energy and reducing accelerationss experienced by the occupants. Fixed landing gear can also be designed to absorb a considerable portion of the energy in vertical impacts.
    e. **P**ost-Crash Factors

       In many crashes, the occupants survive the crash only to succumb to post-crash hazards such as fire, drowning or natural environmental elements such as heat and cold. These conditions are frequently aggravated by an inability to egress the crashed aircraft, due to obstructions within the aircraft, blockage or malfunctioning of emergency exits, or an insufficient number or size of exits.
3. All of the factors listed above should be considered in the analysis of any vehicular crash. Collectively, knowledge gained from individual crashes can be used to detect trends and provide information that can help manufacturers and regulators develop improved means of protecting occupants in a crash. Unfortunately, such data also documents needless injuries and deaths, which subsequently provide the "blood priorities" often-required before necessary improvements in regulations or design are effected.

4. An excellent example of effective technology for preventing injury in crashes, which has been extremely slowly adopted, is the use of crashworthy or crash resistant fuel systems (CWFS/CRFS) in helicopters. These are fuel systems that are designed to completely contain fuel in potentially survivable crashes and, thus, prevent fuel fed post-crash fires. The U.S. Army experience revealed that in Viet Nam era helicopters approximately 40 percent of fatal injuries in survivable crashes were due to post-crash fires. This led the Army to develop and install CWFS on most of its helicopters. Since the introduction of CWFS into Army helicopters, there have only been one or two documented deaths due to thermal injury in survivable crashes of CWFS equipped helicopters. This was a remarkable achievement; particularly considering the cost of retrofitting these systems to Army helicopters was relatively low. For example, the cost of modifying a UH1-H in the mid-1970's was $7,517 with a weight penalty of 160 pounds and a reduction in fuel capacity of only 11 gallons (7). As effective as these systems are, they have only been slowly adopted by other military services, and they are rarely installed in civilian helicopters.
5. Other injury prevention technologies developed by the military such as energy absorbing seats and 5-point restraint systems, though perhaps less effective than CWFS, have also been slow to find their way into civilian applications. This is due to the reluctance of regulators to mandate their use, the reluctance of manufacturers to provide them as standard equipment or as an option, and reluctance of consumers to purchase them when offered as an option.

CONCLUSIONS

The human body is able to withstand remarkable crash forces if provided with appropriate restraint and if protected from collapsing structure and injurious interior objects. Vehicle designers can extend the envelope of survivability through intelligent crashworthiness designs that incorporate means of managing the energy of the crash as well as strengthening the space immediately surrounding occupants. The U.S. Army has proven that these protective technologies can be economically incorporated into helicopters such as the UH-60 Black Hawk, and the crash experience of this helicopter and others, have proven the efficacy of these crashworthiness concepts. The same concepts have been very effectively integrated into Indianapolis and NASCAR racecars with remarkable results. In fact, crash recorders installed in "Indy Cars" indicate that a properly protected human may be able to withstand accelerations considerably in excess of the 40 G limit previously determined by Colonel John Stapp and others. Several Indy car drivers have withstood impacts in excess of 100 G without serious injuries (8).

Some of this technology has been applied to automotive designs and, to a lesser degree, to civilian aircraft. Nevertheless, vehicles could be made considerably safer and more crashworthy. Unfortunately, progress in this area will require heightened awareness of both the problems and the possibilities by the general public, regulators, and legislators. Manufacturers will not be willing to perform the research and development required to incorporate significantly improved crashworthiness into their vehicles unless consumers make safety a priority and reveal their willingness to pay for it. Likewise, legislators and regulators will not be inclined to require significant improvements in crashworthiness or increase research funding in this area unless the public demands it. The potential for improvements in automobile and aircraft crash safety is enormous. Hopefully, the impetus for change will occur through education and increased public awareness.

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