U.S. Army Aviation Applied Technology Directorate (AMCOM RDEC)
Fort Eustis, Virginia 23604-5577
Technology Investment Agreement Modification

1. Agreement Number: DAAH10-02-2-0002

2. Modification Number: P00018

3. Recipient Name and Address: Center for Rotorcraft Innovation
16 Regency Plaza
871 Baltimore Pike
Concordville, PA 19331
Cage Code: 1SAC9

4. Request for Modification. Pursuant to Article IV B, Management of the Project, the purpose of this bi-lateral modification to incorporate the following changes, 1) update the address of the Recipient as reflected in Paragrah 3 above, and 2) update Attachment 2, SARAP Report Requirements/Agreement Deliverables, to include the Helicopter Kinematic Design Criteria for Crashworthiness Analysis. This deliverable will be at no cost to the Government as it was performed under the current Statement of Work and will be delivered with Unlimited Rights to the Government. Accordingly, the following changes are hereby incorporated;

a. Page one of the Agreement is updated as follows:

CENTER FOR ROTORCRAFT INNOVATION
16 REGENCY PLAZA
817 BALTIMORE PIKE
CONCORDVILLE PA 19331

b. Attachment 2 , SARAP Reports Requirement/Agreement Deliverable is updated to include the following in Section D, Graphical representation of deliverables;

Report	#1 Submittal	#2 Submittal	Format	Govt. Rights
Special Technical: 1)Helicopter Kinematic Design Criteria for Crashworthiness	As Required		Recipient	1) Unlimited Rights

7. All other terms and conditions of the Agreement remain unchanged.

FOR CRI

Rande Vause 11/2/2007
Signature and Date
RANDE VAUSE
EXECUTIVE DIRECTOR

FOR THE UNITED STATES OF
AMERICA AVIATION APPLIED
TECHNOLOGY DIRECTORATE

Signature and Date
NANNETTE CICOLINI
GRANTS/AGREEMENTS OFFICER

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

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14. ABSTRACT

This document presents the results of a study commissioned to update the kinematic design criteria for helicopter crashworthiness. The study, conducted by Simula Aerospace and Defense Group, Inc. (Simula), reviewed crash kinematic data over the past 25 years with the objective of identifying new trends in crash parameters and revising the associated design criteria accordingly. The objective of this study is to update the impact design criteria for crashworthiness by studying the crash kinematics of four currently active U.S. Army aircraft; specifically, the CH-47 Chinook, the OH-58, the UH-60, and the AH-64 Apache. No variants of these aircraft were excluded from the study, but a few specific models did not appear in the final list of mishaps. As a part of this update of the impact design criteria, kinematic data were collected and are presented in a manner intended to facilitate easy comparison with earlier studies.

15. SUBJECT TERMS

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FINAL REPORT
ON THE
SURVIVABLE, AFFORDABLE, REPAIRABLE AIRFRAME PROGRAM (SARAP)
AND THE
HELICOPTER KINEMATIC DESIGN CRITERIA FOR CRASHWORTHINESS

Prepared for:

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The analysis contained herein is the expressed opinion of Simula and does not necessarily represent the opinion of CRI or any CRI member

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REVISIONS

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LIST OF ACRONYMS AND ABBREVIATIONS

AI	Autorotation Index
CSDG	Crash Survival Design Guide
FAA	Federal Aviation Administration
GUI	Graphic User Interface
GW	Gross Weight
MIL-STD	Military Standard
MS	Microsoft
P/N	Part Number
SQL	an abbreviation for SEQueL, which is an acronym for Structured English Query Language
TR	Technical Report

Introduction

This document presents the results of a study commissioned to update the kinematic design criteria for helicopter crashworthiness. The study, conducted by Simula Aerospace and Defense Group, Inc. (Simula), reviewed crash kinematic data over the past 25 years with the objective of identifying new trends in crash parameters and revising the associated design criteria accordingly.

Background

The first design guidelines and criteria for rotorcraft were promulgated in the Aircraft Crash Survival Design Guide (CSDG) (1), which was prepared for the U.S. Army. This document was subsequently updated several times, and the latest version, entitled the Aircraft Crash Survival Design Guide (2), was prepared by Simula in 1989. The original design guide was "…a consolidation of design criteria and concepts developed through research programs sponsored by this Directorate over the past 10 years *(1959-1969)* into one report suitable for use as a designer's guide..." Many of the graphics, charts, and tables presented in this report were originally conceived and presented in the first CSDG.

MIL-STD-1290 was created to document recommendations from the CSDG into military helicopter design practice and to set the design criteria that are directly applicable to military aircraft. MIL-STD-1290 was originated in January 1974 and revised in September 1988 (3). Table I of MIL-STD-1290 provides seven crash impact design conditions that are to be used in designing an aircraft's capability to withstand terrain impacts with the landing gear extended.

In 1985, Simula conducted a detailed study (4) of civil rotorcraft crashes for the Federal Aviation Administration (FAA). A team of experts reviewed the rotorcraft accident reports covering a period of 5 years from 1974 through 1978. The report describes the distribution of impact conditions and proposes six impact scenarios for civil aircraft. The report also recommends crashworthiness design criteria for civil rotorcraft.

Two subsequent contributions were made to the field by Dennis F. Shanahan, M.D., M.P.H., in papers published in 1989 (5), and 1992 (6). In the earlier paper, Dr. Shanahan updated the crash kinematics for four then-current Army aircraft; specifically, the AH-1S Cobra, the OH-58C Kiowa, the UH-1H Iroquois, and the UH-60A Black Hawk. Dr. Shanahan used an intensive statistical approach and built on the earlier presentation charts of the CSDG to present his findings. These findings included some of the first statistical findings for the UH-60, which had been designed with crashworthiness as an important consideration. The later paper focused on statistics and lessons learned with the UH-60. Dr. Shanahan's papers relied heavily on the official U.S. Army Accident Database and a statistical approach to extract information. However, Dr. Shanahan would have had access to the original accident reports.

This report represents a similar level of abstraction from the raw data compared to Shanahan. The CSDG and the FAA reports were done by teams of experts with access to the original mishap investigation reports. The personnel on these teams had the background to make informed judgments about the consistency of the recorded impact data with the observed aircraft damage. These teams could and did re-analyze accidents that they felt were inconsistent. The teams were also able to go back to the original data to evaluate hypothesis developed in the course of the investigation. Similar to Dr. Shanahan's study, this investigation has relied entirely on the data recorded in the Army's database. Although it has been tested for internal consistency within a mishap, when inconsistency was found, little could be done other than to discard the mishap from further consideration in the study. The authors recognize that any discarding of cases may create selection bias, but point out that all of the prior studies have discarded cases. The difficulty comes in trying to identify what the nature of the bias actually is. Earlier studies discarded cases on the basis of uncertainty about the data; this study has discarded cases on the basis of internal inconsistency within the data. Naturally, both studies must discard cases where critical information is missing. The authors hope that discarding data only on the basis of quantitative inconsistency will minimize any bias attributable to discarding events. This study, more than any of the prior studies, relies on the skill and consistency of the mishap investigators to generate reliable input data for the analysis.

Objectives

The objective of this study is to update the impact design criteria for crashworthiness by studying the crash kinematics of four currently active U.S. Army aircraft; specifically, the CH-47 Chinook, the OH-58, the UH-60, and the AH-64 Apache. No variants of these aircraft were excluded from the study, but a few specific models did not appear in the final list of mishaps. As a part of this update of the impact design criteria, kinematic data were collected and are presented in a manner intended to facilitate easy comparison with earlier studies.

ACKNOWLEDGEMENTS

The author would like to acknowledge the assistance of Kathryn Kennedy for the statistical analysis. Ms. Kennedy made many useful suggestions as to the appropriate statistical methods to be used and performed the actual statistical tests. The author also would like to thank Mr. Carey Walters of Sikorsky Aircraft for his suggestions on the use of the autorotation index and correlating it to the impact velocity. The author also thanks Mr. Jack Cress of Simula, a former U.S. Marine Corps CH-46 pilot, who answered several questions regarding helicopter operations. Finally, the author acknowledges many important and useful discussions with Mr. Robert Gansman of Simula.

In a special acknowledgement, the author would like to mention that during the final revision stage of the generation of this report, the news was received that James W. "Doc" Turnbow, Ph.D., had passed away at the age of 85. Dr. Turnbow was the originator of many of the concepts used in the aircraft crashworthiness field. A widely recognized expert in the field, Dr. Turnbow was instrumental in the preparation of the first CSDG, and is listed first among its authors.

Data Investigation

The data investigation performed for this analysis consisted of four main stages: querying the database received from the U.S. Army, screening the query results, analyzing the data in the query results, and presenting the data.

Database Description

Information on U.S. Army aircraft accidents is stored in the official U.S. Army Accident Database. This accident information is recorded by the accident investigator(s) using DA Form 2397, Jul 94, and then the data are transferred from the forms into the database. The database used for this study consisted of tables selected from the Official U.S. Army Accident Database and delivered to Simula in a Microsoft (MS) Access file format. The files were converted to the Access 2002 file format, and the analysis was conducted with MS Access contained within MS Office XP Professional. The tables arrived in two databases: one database for the OH-58 and UH-60 aircraft, and the other for the CH-47 and AH-64 aircraft. Both databases included the same set of data tables[1]: AIRCRAFT, AIRCRAFT_STRIKE_PART, BASIC, FLIGHT_DATA, FLIGHT_OPERATION_PHASE, FUSELAGE_DEFORMATION, IMPACT_FORCE, IN_FLIGHT_IMPACT, IN_FLIGHT-OBSTACLE, IN_FLIGHT_WIRE_STRIKE, LARGE_COMP_DISPLACEMENT, NARRATIVE, ROTATION_IMPACT, TERRAIN_GENERAL, TERRAIN_IMPACT, TERRAIN_OBSTACLE, and TERRAIN_SURFACE. Each table in turn included anywhere from one or two parameters to up to a dozen or more. The common tie for all the data related to a particular mishap is the CASE_NUMBER. Where multiple aircraft were involved, the data could be separated by AIRCRAFT_SERIAL_NUMBER.

Other tools were used to understand and select the data. The analyst used the Aviation Data Dictionary by Form and Block to relate information in the database back to the original recording document DA Form 2397 Jul 94. A copy of Department of the Army Pamphlet 385-40 (7) was also used as a reference for understanding the guidance given to the investigator in recording the information.

Database Queries

Prior to actually creating and executing the study queries, the parameter ANALYSIS in the table NARRATIVE was reviewed and a new parameter, IS_CRASH, was created and recorded in this table. The ANALYSIS parameter is a short verbal summary of the mishap. Many mishaps are recorded that result in substantial aircraft damage or injury, but are not the result of crash impact. The verbal summary provides information to assist in determining whether the mishap should be considered a crash for purposes of this study. Each CASE_NUMBER in the table was assigned one of three values for the parameter IS_CRASH based on reading the analysis: “Yes”, “No”, or “Maybe”. A subsequent query was created to extract the CASE_NUMBERS with the IS_CRASH values of “Yes” and “Maybe”, along with the associated impact velocity and angle data. Based on these data being sufficient to confirm at least a hard landing, the “Maybe” cases were included in “Yes.” If the data were absent or not indicative of a crash, the case was

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[1] Database variables (fields) are capitalized and the words are connected with underlines, as FLIGHT_DATA. Some field names are not unique; i.e., the same field name appears within different database tables. These fields are identified with both the table name and the field name separated by a period, as AIRCRAFT.CASE_NUMBER. These conventions are used in the database and the author has retained them in this report.

assigned to "No." Events where the aircraft made a "hard landing", but was subsequently flown to another location were coded "No", even though subsequent investigation might find sufficient damage for the event to be classified as an "A" or "B" event. The queries include crashes of all three survivability levels: survivable, partially survivable, and non-survivable.

An inclusive query was created that retrieved all of the data necessary to conduct the proposed study. Although the query was capable of capturing all of the 43 parameters (See Table 2.1) requested, the output of the query proved to be rather unmanageable. The number of parameters is so large partly because some quantities, such as velocity, require two parameters to be captured; i.e., a quantity and a direction. Many of the parameters have multiple values recorded for a given case number; for example, the weight of the aircraft might be recorded for several phases of the flight, and likewise several values for NEW_PHASE, which is the phase of the flight descriptor leading up to the crash, were frequently recorded. Due to the nature of the database, when recording multiple values for a single parameter, the number of records returned is a product, rather than a sum, of the number of different values entered. Thus, some mishaps had hundreds of records (similar to rows in a spreadsheet) associated with the same case number. Even though Access has a utility to export data to Microsoft Excel (which is a spreadsheet), it was still rather cumbersome to work with such a large array. Although these queries were saved as deliverables, other, smaller queries were actually used to perform the analysis. Smaller, less-inclusive queries were created to extract information targeted at specific aspects of the study; e.g., impact velocity and angles.

Table 2.1. Parameters in the Master Query

Table	Parameter	Comment
All tables	CASE_NUMBER	Database key
AIRCRAFT	MTDS	Aircraft type
AIRCRAFT	AIRCRAFT_SERIAL_NUMBER	
NARRATIVE	IS_CRASH	Created by analyst
NARRATIVE	ANALYSIS	Summary of mishap
BASIC	CATEGORY	A or B for this study
AIRCRAFT	MISSION_1	
FLIGHT_OPERATION_ PHASE	NEW_PHASE	
FLIGHT_DATA	AGL_ATTITUDE (sic)	Above Ground Level
FLIGHT_DATA	AIRCRAFT_WEIGHT	Took lowest value as nearest to emergency
FLIGHT_DATA	MSL_ATTITUDE (sic)	Mean Sea Level
FLIGHT_DATA	AIRSPEED_KIAS	
AIRCRAFT	SURVIVABILITY	1= Survivable, 2 = Partially survivable, 3 = Non-survivable based on cabin volume retention, not actual injuries
TERRAIN_GENERAL	CHARACTERISTICS	
TERRAIN_SURFACE	SURFACE	
BASIC	SLOPE_DEGREES	Form: Level or __ deg. Often left blank. Is not directional relative to flight path.
TERRAIN OBSTACLE	OBSTACLE	
TERRAIN_IMPACT	GROUND_SPEED	

Table 2.1. Parameters in the Master Query (cont'd)

Table	Parameter	Comment
TERRAIN_IMPACT	GROUND_ACCURATE	Refers to relative accuracy of three variables. Ground speed, vertical speed, and flight path angle. Least-accurate coded F, other two coded T.
TERRAIN_IMPACT	VERTICAL_SPEED	
TERRAIN_IMPACT	VERTICAL_SPEED_DIRECTION	Up or down
TERRAIN_IMPACT	VERTICAL_ACCURATE	See GROUND_ACCURATE
TERRAIN_IMPACT	FLIGHT_PATH_DEGREE	
TERRAIN_IMPACT	FLIGHT_PATH_DIRECTION	
TERRAIN_IMPACT	FLIGHT_PATH_ACCURATE	See GROUND_ACCURATE
TERRAIN_IMPACT	IMPACT_DEGREE	
TERRAIN_IMPACT	PITCH_DEGREE	
TERRAIN_IMPACT	PITCH_DIRECTION	
TERRAIN_IMPACT	ROLL_DEGREE	
TERRAIN_IMPACT	ROLL_DIRECTION	
TERRAIN_IMPACT	YAW_DEGREE	
TERRAIN_IMPACT	YAW_DIRECTION	
ROTATION_IMPACT	PITCH_DEGREE	
ROTATION_IMPACT	PITCH_DIRECTION	
ROTATION_IMPACT	ROLL_DEGREE	
ROTATION_IMPACT	ROLL_DIRECTION	
ROTATION_IMPACT	YAW_DEGREE	
ROTATION_IMPACT	YAW_DIRECTION	
IMPACT_FORCE	VERTICAL_G	
IMPACT_FORCE	VERTICAL_DIRECTION	
IMPACT_FORCE	LONGITUDINAL_G	
IMPACT_FORCE	LONGITUDINAL_AREA	
IMPACT_FORCE	LATERAL_G	
IMPACT_FORCE	LATERAL_DIRECTION	

Number of Cases Extracted and Used

Once the mishaps had been identified as being crashes or not, the first major query executed was to retrieve the crash kinematic data together with related information such as survivability, slope, and terrain obstacles. The results of this query for each aircraft were exported to a spreadsheet in MS Excel software for consistency checks. In Table 2.2, the number of aircraft events identified as crashes is shown as the "Cases Extracted." The cases in Table 2.2 include events at all three levels of survivability.

Table 2.2 Number of records extracted by aircraft type

Aircraft	Cases Extracted
CH-47	45
OH-58	309
UH-60	94
AH-64	64
TOTAL	**512**

Most of the queries returned multiple records (rows of data on a spreadsheet) associated with each case number. In the mishaps where a collision between aircraft occurred, two aircraft serial numbers and two records appear, and the data for both aircraft were retained as two separate records with the same case number. Multiple records are the result of multiple values being recorded for a particular parameter. The effect on the query output is multiplicative with respect to the number of parameters having duplicate values and the number of duplicate values. Thus, many case numbers returned dozens of records, and a few returned hundreds.

After exporting the query results to the corresponding spreadsheet, the duplicates were reduced to one record for each case and aircraft serial number. Many records were true duplicates and these were easily eliminated. However, it was desirable to retain some information in duplicate records. Multiple values for the TERRAIN_SURFACE.SURFACE, TERRAIN_OBSTACLE.OBSTACLE, and NEW_PHASE were recorded in the spreadsheet by creating a second field for each and labeling them as primary and secondary fields for the same variable.

<u>Inclusion and Consistency Reviews</u>

The inclusion and consistency checks of the query output entailed reviewing the kinematic data to ensure, first of all, that most of the critical variables were present for each mishap, and second, that the values of variables were consistent within the mishap. To accomplish these reviews, several new parameters were added to the spreadsheet. The velocity and direction (e.g., VERTICAL_VELOCITY, which would give the magnitude of the velocity and VERTICAL_DIRECTION, which would be coded “up” or “down”) variables were combined into a single algebraic parameter consistent with the aircraft reference frame. Likewise, angle parameters were combined from a pair of variables to a single algebraic parameter. A parameter was calculated by subtracting the SLOPE_DEGREES from the IMPACT_DEGREES. This parameter should be approximately equal to the FLIGHT_PATH_DEGREES. The values of GROUND_SPEED and VERTICAL_SPEED were combined to determine a resultant velocity angle. The angle was compared to the value recorded for FLIGHT_PATH_DEGREES. The magnitude of the velocity resultant was calculated. Using these parameters, a brief protocol was written and used to review the data. This protocol was:

- Compare Algebraic Flight Path Angle to IMPACT DEGREES - SLOPE_DEGREES (= FLIGHT_PATH_DEGREES). If they are within 15 deg, OK. Also look at FLIGHT_PATH_ACCURATE: If ACCURACY = F (FALSE), then use IMPACT_DEGREES – SLOPE_DEGREES, if available.
- Compare Resultant Velocity Angle to FLIGHT_PATH_DEGREES. If very different, try to determine / understand why. Check the ACCURACY variables. If one of the component velocities has an "F" accuracy, adjust that velocity to bring the Resultant Angle into agreement. If a very large adjustment is necessary, discard the mishap.
- Compare the magnitude of the Resultant Velocity to the Airspeed prior to the accident. If the two are dramatically different, review the Narrative. Circumstances may exist where the two velocities are quite different either way, but the reason for the difference should be clear from the mishap summary.
- If discrepancies cannot be resolved or seem very inconsistent with the Narrative, then drop the event.

Application of these consistency criteria reduced the number of cases retained for each aircraft as reported in Table 2.3. Even after this selection process, a few cases lacked certain data items; thus, the number of cases used in specific analysis may be slightly lower than the numbers above. The case numbers of the retained events were extracted as a text list that could then be turned into an SQL (Structured English Query Language) statement. Behind the Graphical User Interface (GUI) of MS Access, the program operates in SQL and statements can be modified directly in SQL. The most expedient way of querying the database for just those events that were selected as usable crashes was to create the query in the Design view of MS Access and then insert the list of selected events as a constraint to the SQL statement. The cases in Table 2.3 continue to include all levels of survivability.

Table 2.3. Number of cases extracted and used for each aircraft type

Aircraft	Cases Extracted	Cases Used	% of Extracted Cases Used
CH-47	45	25	56
OH-58	309	178	58
UH-60	94	60	64
AH-64	64	44	69
TOTAL	**512**	**307**	**62**

Table 2.4 indicates that the OH-58 represents 58 percent of the mishaps used in this study, and consequently tends to dominate all of the combined data presentations. Table 2.5 elaborates on Table 2.4 by providing the reader with a breakout by model for each aircraft type. These breakouts are important, especially for the OH-58 where the D model has a significantly different rotor system than the earlier versions.

Table 2.4. Fraction of mishaps by aircraft type making up the study data

Aircraft	Cases Used	Percent of All Crash Cases
CH-47	25	8
OH-58	178	58
UH-60	60	19
AH-64	44	14
TOTAL	**307**	**100**

Table 2.5. Mishap aircraft sub-types

No.	Sub-type	No.	Sub-type	No.	Sub-type	No.	Sub-type
3	CH-47A	123	OH-58A	43	UH-60A	40	AH-64A
2	CH-47B	24	OH-58C	12	UH-60L	4	AH-64D
12	CH-47C	9	OH-58D	1	MH-60A		
5	CH-47D	6	OH-	1	MH-60K		

			58DR			
3	MH-47E	14	OH-58DI	2	MH-60L	
		1	JOH-58A	1	EH-60A	
_		_1	JOH-58C	__		__
25		178		60		44

Database Query Results

The following sections present the results of the database queries as tables and graphs. Some comparison is also made to two previous studies: the series of Crash Survival Design Guides culminating with the 1989 edition (1,2), and the 1992 paper by Shanahan and Shanahan (6). The impact speed and velocity components will be addressed first, followed by the aircraft angles at impact, then the impact angle, and finally other parameters such as terrain and impact obstacles. Figure 2-1 shows the aircraft coordinate system and directions that will be used throughout this report (2).

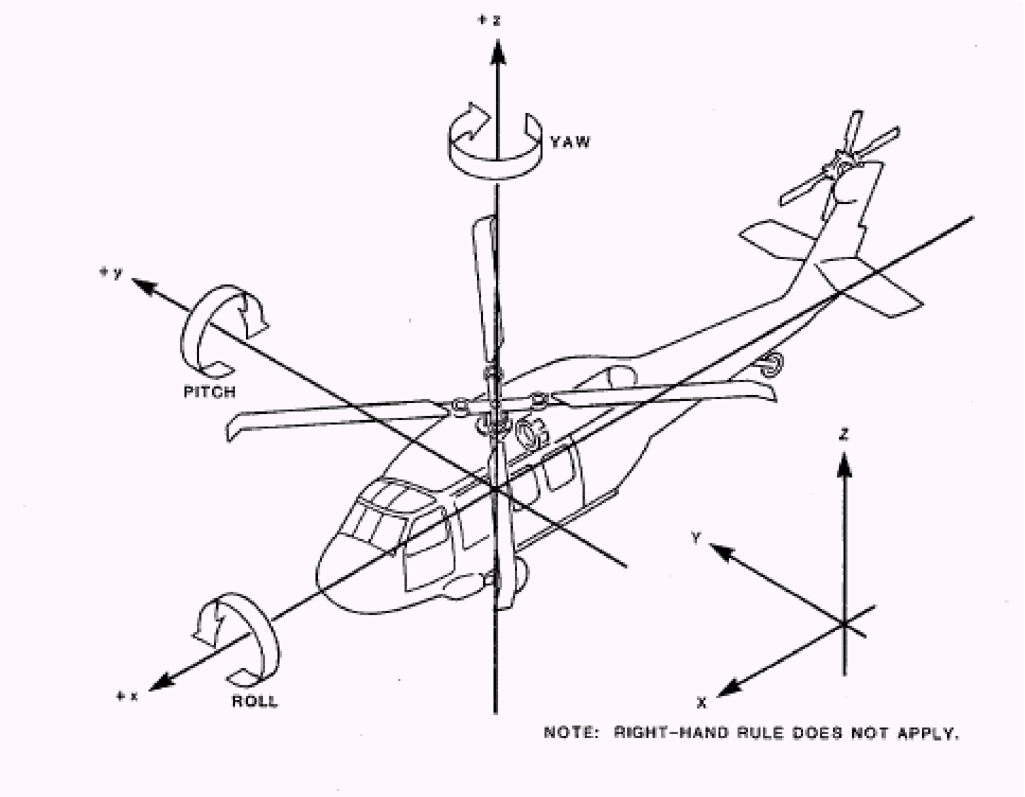

Figure 2-1. Aircraft coordinate system and directions (Reference 2).

Speeds in Earth Reference Frame[2]

The speed change in this analysis is taken directly from the database parameters TERRAIN_IMPACT: GROUND SPEED and TERRAIN_IMPACT: VERTICAL_SPEED. The parameters are taken from DA FORM 2397-6-R, Part VII, In-flight or Terrain Impact and Crash Damage Data (7). The instructions for Block 2a state: "Estimate or analytically determine and enter the ground / horizontal velocity (knots) at the instant of the major impact." There is no provision in the form for recording the velocity following the major terrain impact; consequently, the value is not the true "velocity change," but rather the velocity at the time of impact. The Shanahan paper (5) also used the database as its source for velocity information; therefore, the speeds in this section of the study should be comparable to those in the Shanahan study. One type of event where the speed change of the major impact can be determined is the event where the major impact occurs in-flight, followed by a terrain impact close by. By taking the difference between the in-flight impact velocity and the terrain impact speed, the speed change of the major impact could be determined. The speed in this study is the aircraft's speed at the time of terrain impact, as defined in the FORM 2397-6 instructions It should also be noted here that the ground speed and vertical speed are recorded regardless of the aircraft attitude; these parameters record the speed at which the aircraft impacts the ground. The attitude of the aircraft will be taken into account in subsequent sections, when velocities are discussed.

Plots of the speed data for survivable and partially survivable events will be presented first, because these plots can be directly related with past research work such as the 1979 Crash Survival Design Guide (8) and Shanahan's work (5).

Cumulative Percent Plots of Speed for Survivable and Partially Survivable Crashes

The speed change during the major impact is often difficult to ascertain; more often than not the speed of the aircraft prior to the major impact is used as the speed change for the crash. Speed determines the kinetic energy that must be absorbed in the impact and thus is an important design consideration. In looking at the circumstances from a large number of crashes, the CSDG presents the speed changes in ascending ranked order. Presented in this manner, the designer can select a design criteria or level of protection and readily see how many or what percentage of mishaps will be included by the design decision.

The speed data for two primary directions were converted to absolute values and then sorted into ascending order to create the plots showing the speed in terms of cumulative percent. The cumulative percentile for each data point was then calculated by dividing its sequence number by the total number of the data points in the set. The statistical approach of determining the mean and standard deviations for the data set and then estimating the 95th percentile assumes a normal distribution of the data that was not appropriate for these data sets, because the data are not normally distributed. Each speed value is plotted against its corresponding cumulative percent

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[2] The author uses the term "speed" in referring to the time rate of change in position for the longitudinal and vertical directions in the earth reference frame and uses "velocity" for the same parameter in the aircraft reference frame. The difference in terminology is done to remind the reader which reference frame is in use. In physics, speed is generally a scalar, whereas velocity is a vector. This difference is partially reflected in the author's choice of terminology.

value (See Figures 2-2 and 2-3)[3]. The 95th-percentile line is simply a vertical line plotted at 95 cumulative percent and is provided as a reference for the reader. The initial set of three charts include only survivable[4] and partially survivable (S = 1 & 2) events. A separate curve is presented for each aircraft type. Table 2.5 provides the reader with a breakout of models for each aircraft type.

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[3] The curves for Shanahan and 1979 CSDG data were digitized from the original source publications or reprints thereof. The curves here represent the smooth curves published and data points used to generate these curves are pairs extracted from the digitizing, not the raw data from those studies. The "curves" for the data in this study are actually straight line segments connecting data points.

[4] Survivable (S=1) - Crash forces imposed upon the occupied area of the aircraft must be within human tolerance AND all portions of the occupied volume must remain intact and occupiable. Partially survivable (S=2) – Some seat positions meet the survivable criterion. Non-survivable (S=3) - No seat positions meet the criterion. Actual injuries are NOT the determining factor.

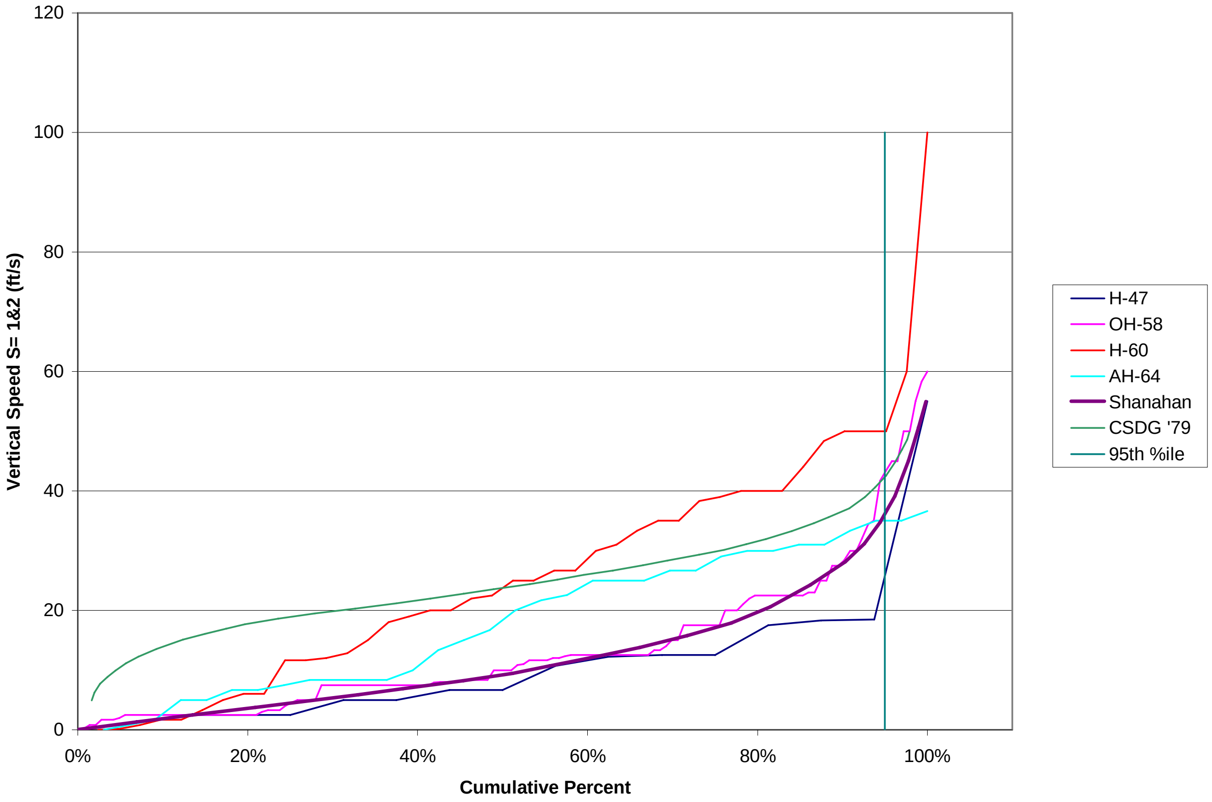

Figure 2-2. Vertical impact speed cumulative percent survivable events (S= 1 & 2) (eRef. 27[5]).

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[5] eRef. is intended to assist the reader with an electronic copy of the associated data. The eRef refers to the electronically stored source data with a file name for the Excel workbook and a worksheet name.

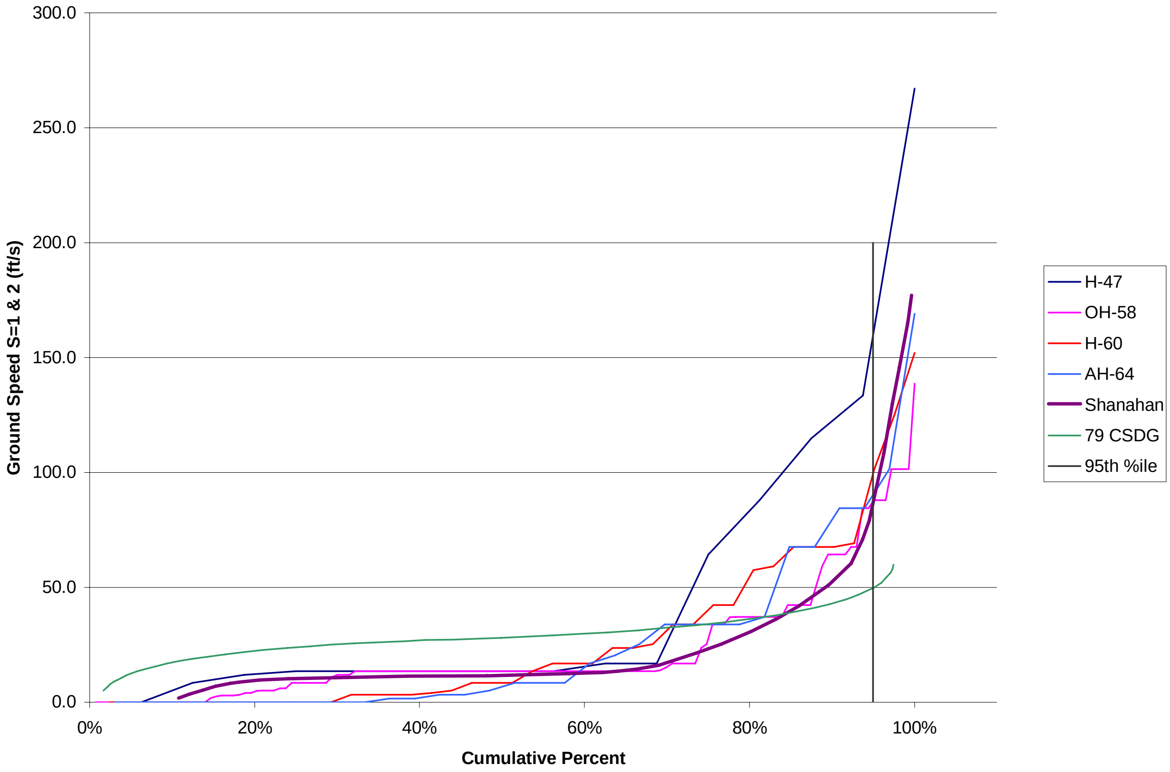

Figure 2-3. Ground speed cumulative percent survivable events (S= 1 & 2) (eRef. 28).

The early editions of the Design Guide chose the 95th percentile on the curve of survivable and partially survivable crashes as a reasonable value to set for crashworthy designs. Thus, the crashworthiness objective is to design aircraft so that the occupants will survive in a crash occurring at speeds up to the 95th percentile of survivable crashes experienced by aircraft built prior to the creation of crashworthiness standards. In later editions of the Design Guide, this 95th-percentile reference was dropped due to the concern that it would lead to “creeping” crashworthiness. The authors of the later revisions realized that future studies to update the crash kinematics (such as this one) would include data from new mishaps, and that many of these new mishaps would involve aircraft designed to the crashworthiness standards. These crashworthy aircraft will presumably enable their occupants to survive some events occurring at speeds even higher than the design standards. Thus, if one performs the similar algorithm to obtain a new crashworthiness speed target, the objective will be raised every time the crash data are revisited. The authors of the later revisions of the Design Guide felt that this incremental increase in the standards would quickly lead to impractical levels of crashworthiness that would unduly penalize the performance of the aircraft for relatively small incremental reductions in injuries and fatalities. The 95th-percentile levels are marked on the cumulative curves merely as a reference point; on most curves, the 95th-percentile level falls well into the region where the velocity is rising rapidly with each incremental event. The reader may infer that only a few points are driving the sharp increases above the 95th-percentile level from the sharp changes in the slope of each line segment.

Regarding vertical impact speed, the first effect that the reader notices in looking at Figure 2-2 is that the UH-60 experiences survivable crashes at consistently higher vertical velocities than the other aircraft. Shanahan discusses this result extensively in Reference 6. The reader will also note that the UH-60 lies above the CSDG '79 curve from about the 50th percentile on up. This relative position means that the UH-60 design is succeeding in delivering survivability even beyond the speed curves presented in 1979 version of the CSDG and effectively beyond the speeds used to set the benchmarks for crashworthy design. The reader can also see that the AH-64 is delivering survivability well above the OH-58 and the CH-47.

With respect to ground speed impact velocity, the reader will see that the CH-47 has the highest ground speeds in survivable or partially survivable accidents. Personnel in the rear of the CH-47's may benefit from its long cabin area. When the aircraft crashes in the forward direction, the occupants toward the rear will benefit from the extensive crush distance of the long fuselage. Both of the helicopters designed to crashworthiness requirements exceed the '79 CSDG curve, especially above the 80th-percentile velocities.

Cumulative Percent Plots of Speed for All Crashes

Although there is little or no prior work to which these plots may be compared, the corresponding cumulative percent plots are presented below for all crashes in the study, that is including S= 1-3. These plots reveal little about the crashworthiness or survivability of the aircraft; rather they present the most extreme impact speeds experienced by these aircraft.

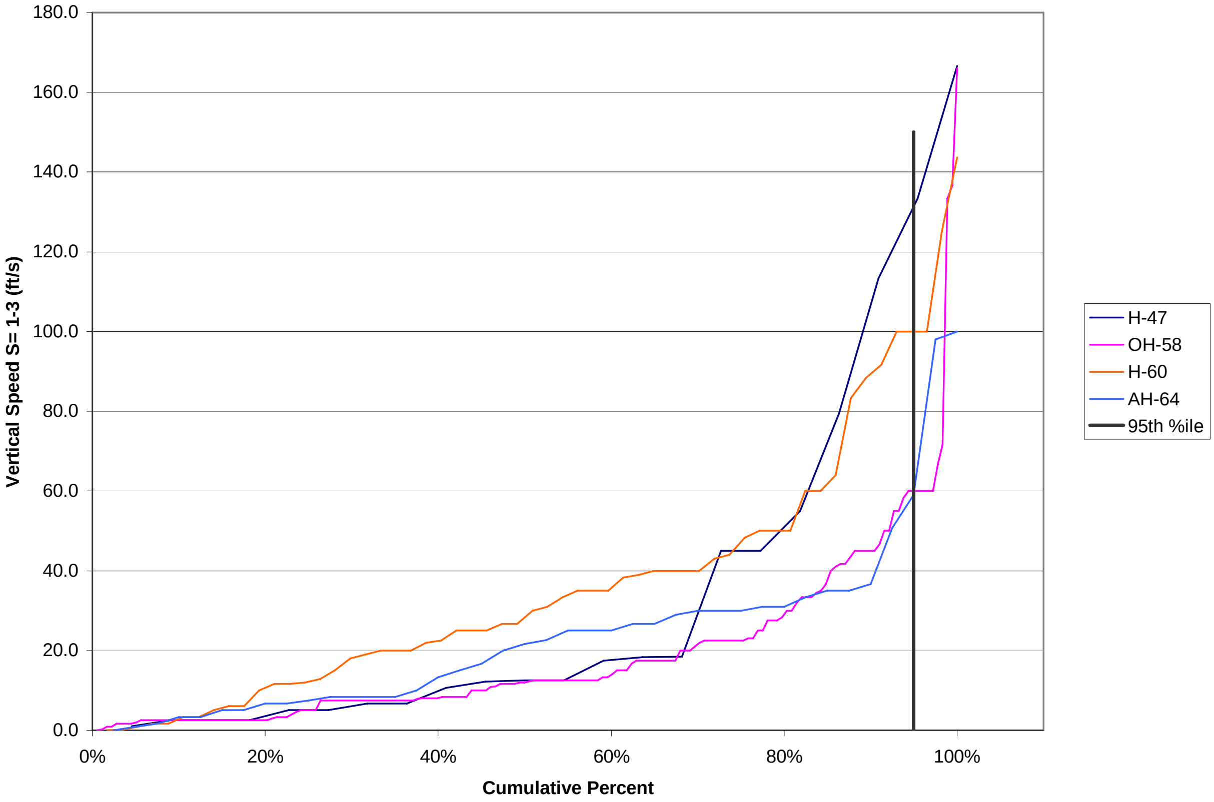

Figure 2-4. Vertical impact speed cumulative percent for all events (S= 1 - 3) (eRef. 29).

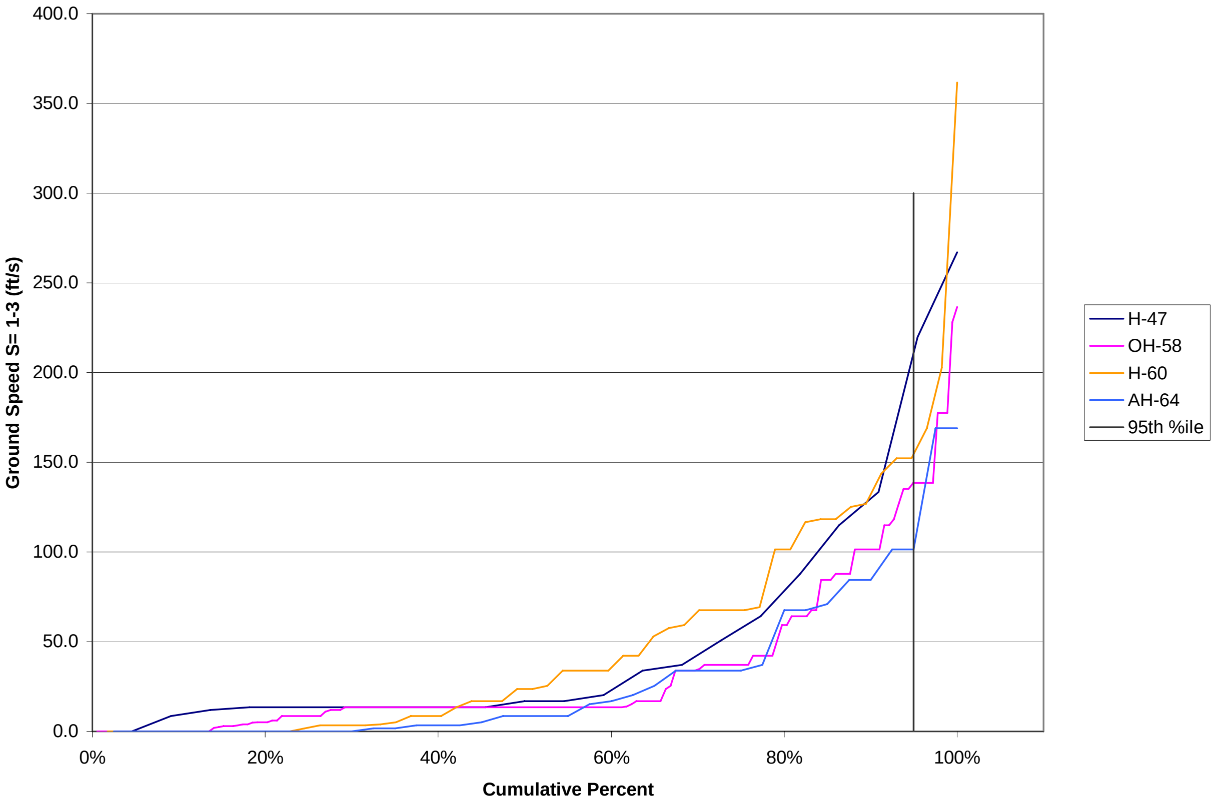

Figure 2-5. Ground speed cumulative percent for all events (S= 1 - 3) (eRef. 30).

In the vertical direction (Figure 2-4), the CH-47 experiences the highest crash speed, which is substantially higher than the highest speed for the survivable crashes. The UH-60 also reveals high crash speeds indicating that impacts occur well beyond the survivable limit. The OH-58 has one or two very high crash speeds, but these represent a relatively small fraction of all the OH-58 crashes. Interestingly enough, the AH-64 shows a relatively low vertical crash speed curve comparable to that of the OH-58 and the difference in speed between the top 10 percent of survivable crashes and the top 10 percent of all crashes is not that different.

Figure 2-5 shows the corresponding curves for the ground speed in all crashes. Once again, the CH-47 is high, but the UH-60 reveals one extremely high (perhaps not credible) event. Once again, the AH-64 is low, similar to the OH-58 in impact speeds.

Velocities in the Aircraft Reference Frame

The velocities of most interest to the crashworthiness community are those in the aircraft reference frame, for it is these velocities that correlate best with the deceleration forces applied to the primary axes of the aircraft. These forces are of interest for protecting the occupants because the human tolerances to acceleration are tabulated along the primary axes of the occupant. The variables recorded in the TERRAIN_IMPACT table of the database are

GROUND_SPEED, VERTICAL_SPEED, and the impact angles expressed as aircraft attitude angles, pitch, roll and yaw. It should be noted that no lateral velocity is recorded in the database.

Conversion from Earth reference frame speeds to Aircraft reference frame velocities

Transforming the two ground coordinate system velocity components recorded in the database into the aircraft coordinate system is a vector transformation accomplished using a transformation matrix. The velocity is expressed as a three-element matrix, and the transformation is expressed as a three-by-three element matrix. There is a transformation matrix for each angle change: pitch, roll, and yaw. These three transformation matrices were combined into a single transformation matrix by multiplying them together. Unfortunately, matrix multiplication is not associative, so order affects the outcome. No convention was found for the order of applying the angles. However, after careful consideration and some experimentation, the sequence selected was to multiply the roll transformation matrix times the pitch transformation matrix, and then multiply that result by the yaw transformation matrix, to create a single transformation matrix. The multiplication of this transformation matrix was expressed as operations in three MS Excel worksheet cells. Although no lateral velocity was recorded in the database, a column was created with blank cells, and the transformation cells used the cells with the two ground coordinate velocities and the blank lateral velocity cell to create three velocity components in the aircraft coordinate system. Thus, even though there was no lateral velocity recorded; after the coordinate transformation, a non-zero lateral velocity component was often created. The transformation, as expressed in MS Excel, was tested on several simple velocity component and angle combinations, such as 45 deg nose down and up, 45 deg nose right and left, and 45 deg roll right and left, combined with pure forward, pure lateral, and pure vertical velocities. All of these tests produced reasonable results.

In order to accomplish the transformation described above, a complete set of five values was required for the mishap; i.e., ground speed, vertical speed, and pitch, roll, and yaw angles at impact. If any one of these was missing, the transformation generally failed to give a result and that mishap was consequently dropped out of consideration for analysis of airframe velocity parameters. The OH-58 had 11 events missing one or more parameter; the dropping of these mishaps explains some of the discrepancies in mishap counts.

Velocity Cumulative Percent Plots

The following three figures present cumulative percentile curves for the impact velocities along the three axes of the aircraft reference frame. While these velocity curves in the aircraft reference frame are not, strictly speaking, comparable to the analysis performed in the '79 CSDG nor to Shanahan's work due to the differences in reference frame, the curves are placed on these graphs as the best available comparisons. No comparison curves are available for lateral velocity. The cumulative percentiles are calculated the same way as for the speeds; the absolute value of each velocity is taken and then the resulting values are placed in ascending order. The sequential number of each data point is divided by the total number of data points to determine a percentile for each velocity data point. The distribution of positive and negative velocity values along each axis will be presented in a later discussion.

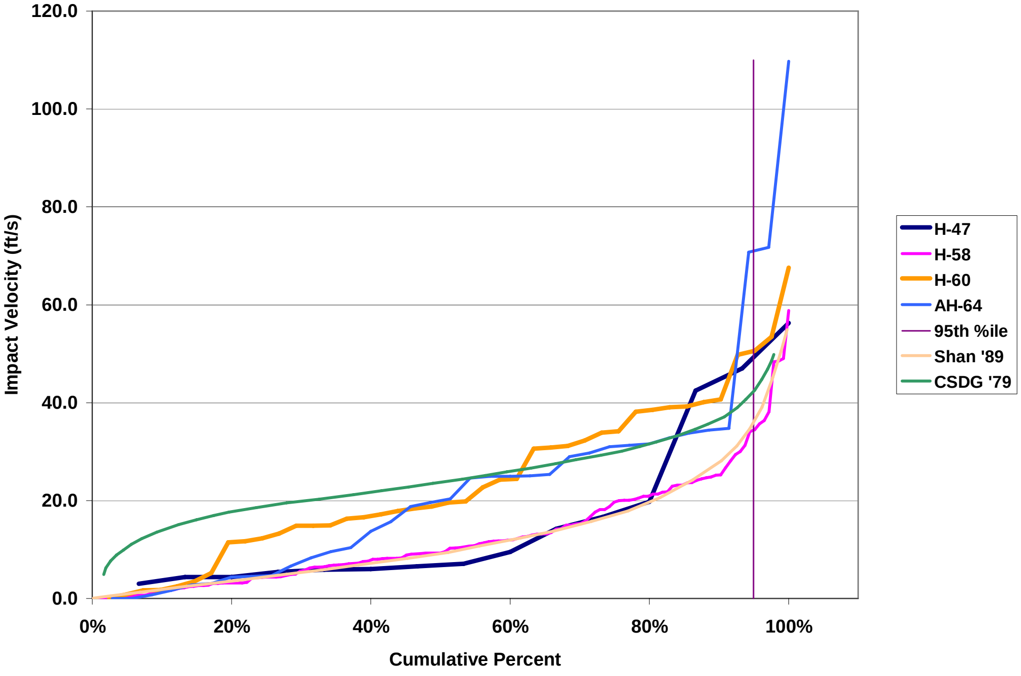

Figure 2-6. Vertical impact velocity cumulative percent survivable events (S= 1 & 2) (eRef. 21).

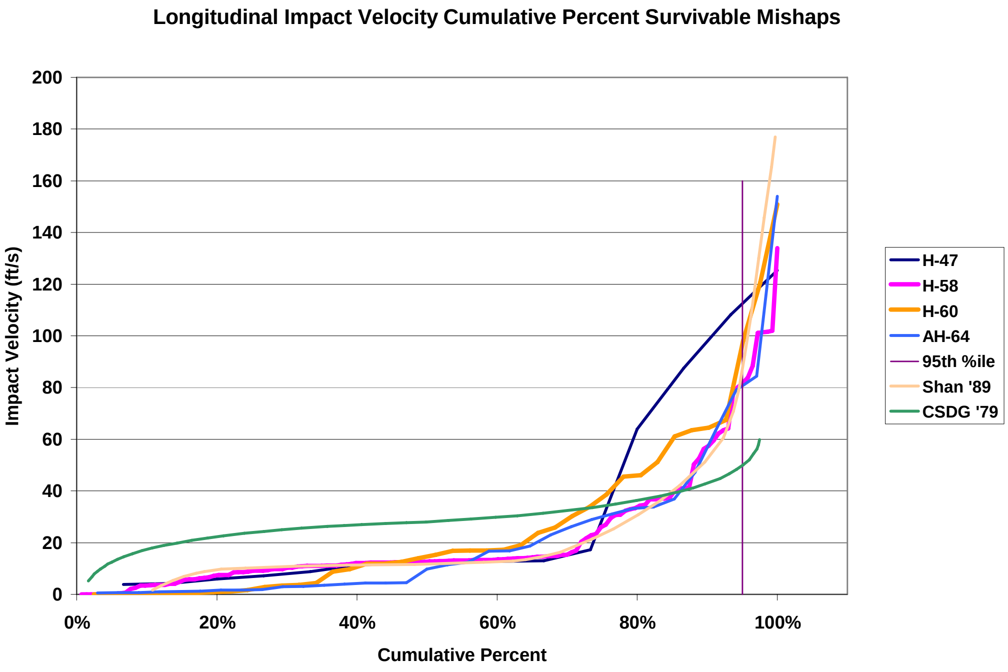

Figure 2-7. Longitudinal impact velocity cumulative percent survivable events (S= 1 & 2) (eRef. 22).

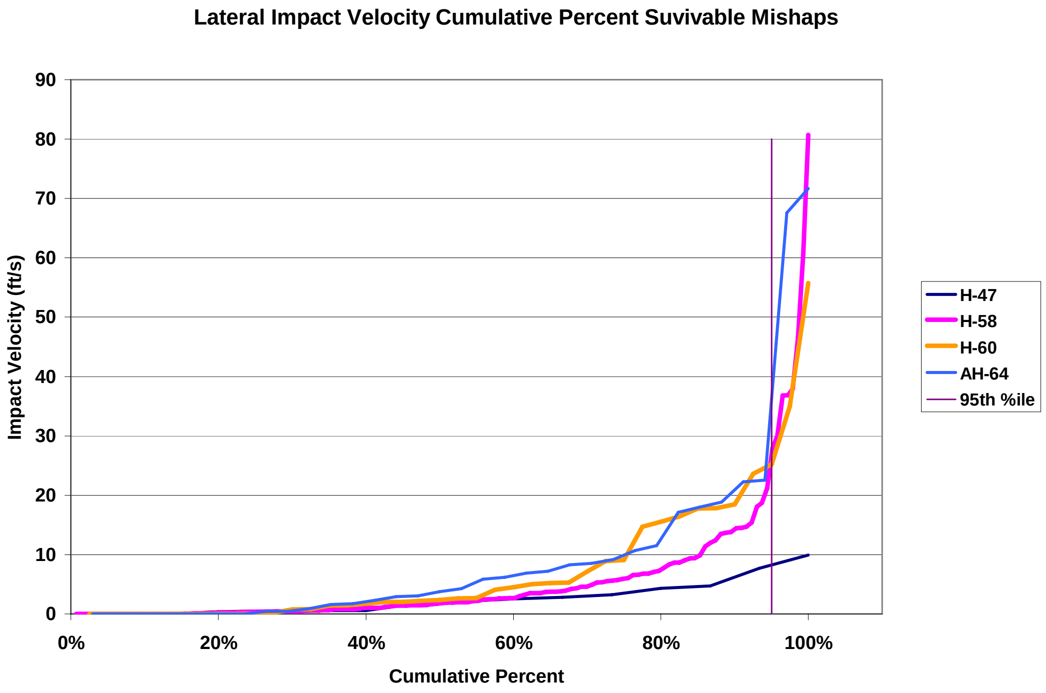

Figure 2-8. Lateral impact velocity cumulative percent survivable events (S= 1 & 2) (eRef. 23).

The vertical impact velocity plot (Figure 2-6) has several features worthy of remark. The AH-64 demonstrates high vertical velocities in the aircraft reference frame, whereas it was relatively low in vertical impact speed. This difference may indicate that the survivable impacts for the AH-64 are those where it crashes most closely to the normal flight attitude, thus giving the large velocity vector along the Z axis. Comparing the UH-60 curves on the two different plots, one finds little difference, suggesting that for the UH-60, the attitude at impact has less effect on survivability or that fewer crashes occur at extreme attitudes. Looking just at the vertical velocity curve, the UH-60 and AH-64 are quite similar, suggesting that in this reference frame, the two aircraft have similar impact characteristics. Both aircraft are impacting at significantly higher vertical velocities than the OH-58 from about the 40th percentile on up.

In the longitudinal impact velocity data (Figure 2-7), the H-47 presents a sharp discontinuity in the data; however, the steep part of this curve is only 4 data points out of a total of 25. The velocities jump from 17 ft/sec to 64 ft/sec and then continue upward in roughly 20 ft/sec jumps. There is little in the longitudinal velocity curves to differentiate between the aircraft types. The UH-60 crashes in the range from 75th to 90th percentile run about 15 to 20 ft/sec higher than the other aircraft, but then rejoin the other aircraft. This bulge may represent a larger fraction of mission time transiting at higher velocity than the other aircraft types.

There are no comparable lateral impact velocity curves from the Shanahan paper or CSDG ’79 to plot over the curves for the aircraft in this study. The H-47 displays very low lateral velocities for survivable crashes. Possible explanations for this result were not investigated. The OH-58 performs remarkably well at the upper end of the curve, but the two helicopters designed to higher crashworthiness standards out-perform it in the range from the 60th to 95th percentiles.

The following three figures (Figures 2-9 through 2-11) present cumulative percent velocity curves, which include all mishaps regardless of survivability. These curves are provided for the benefit of the designer and those who may be considering revisions to the crashworthiness design guidelines. The differences between the two sets of curves reflect the kinematics of events beyond the objectives of the current crashworthiness standards.

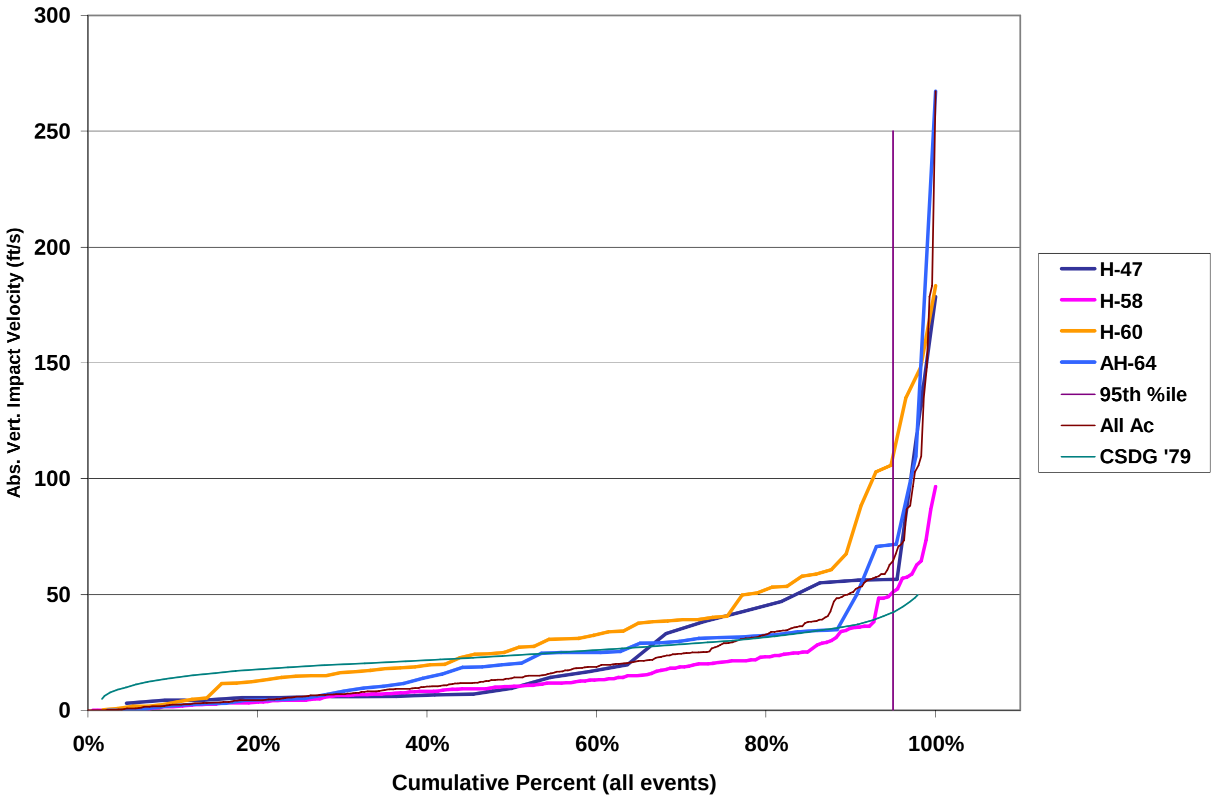

Figure 2-9. Vertical impact velocity cumulative percent including all mishaps (eRef. 1).

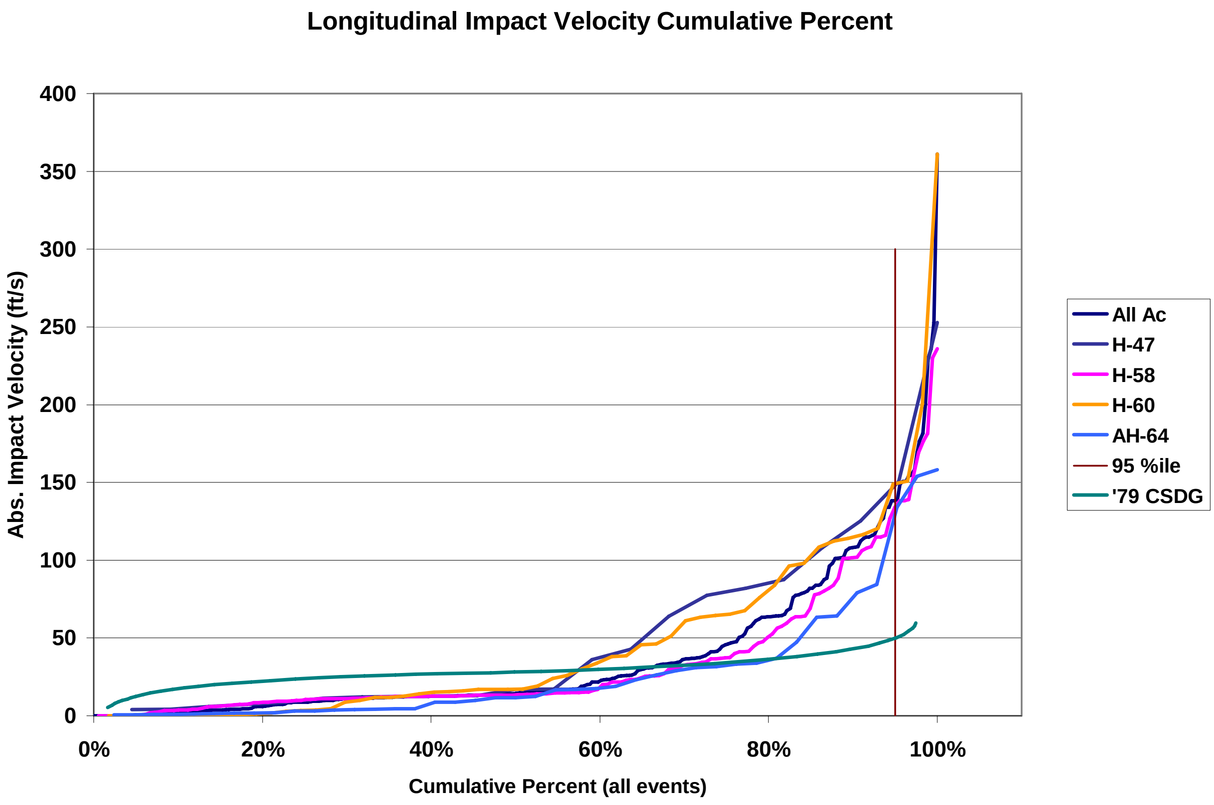

Figure 2-10. Longitudinal impact velocity cumulative percent including all mishaps (eRef. 2).

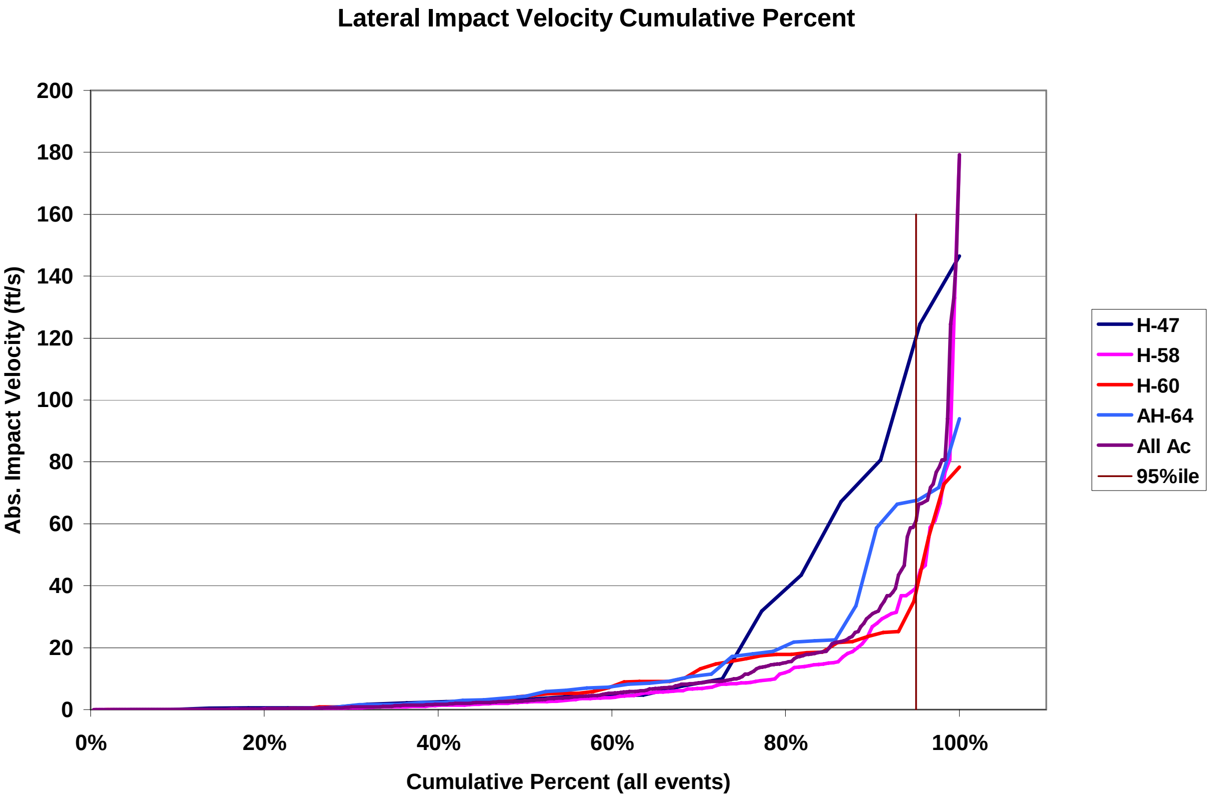

Figure 2-11. Lateral impact velocity cumulative percent including all mishaps (eRef. 3).

The cumulative percent curves above include all events regardless of survivability, and thus do not lend themselves to a direct comparison with the 1979 CSDG curves or with the Shanahan analysis. Table 2.6 and Figures 2-12 and 2-13 address comparisons between the studies. The Shanahan paper has analysis that includes all events, as well as just the survivable mishaps. Table 2.6 compares the mean horizontal and vertical velocities calculated in the Shanahan study and to those calculated in this study. Looking at the values in Table 2.6, the lower vertical values stand out, compared to the vertical values in the Shanahan study. These lower values can be explained by reviewing the individual data points in this study for the UH-60, where half a dozen very high (> 75 ft/sec) negative-vertical-velocity events can be seen. This type of event would be those where the helicopter struck the ground at a high rate of speed in an inverted attitude. Even though the Shanahan study numbers include “all mishaps” (even non-survivable), the Shanahan study did exclude mid-air collisions and other events that may have involved free falls from greater than 100 ft. This study includes these types of events.

Figure 2-12 compares the vertical velocity curves from Figure 4 of the ’79 CSDG (Reference 7) and the vertical velocity curve in Figure 6 of the Shanahan study (Reference 6) with a comparable compilation of velocities for all four aircraft in this study, including only events rated as survivable or partially survivable (S = 1 or 2). Figure 2-13 compares the forward velocity curves from Figure 5 of the CSDG and Figure 7 of the Shanahan paper (Reference 6) to a comparable compilation of velocities for all four aircraft in this study, including only events rated as survivable or partially survivable (S = 1 or 2). Thus, the cumulative velocity curves in Figures 2-12 and 2-13 are as comparable as it is practical to make them.

Table 2.6. Comparison of mean velocities between studies

	Mean vertical velocity - All mishaps			
	Shanahan		**This Study**	
Aircraft	**Velocity (ft/sec)**	**Mishaps (No.)**	**Velocity (ft/sec)**	**Mishaps (No.)**
OH-58	14.1	85	6.9	178
UH-60	52.5	26	9.3	57
CH-47			8.7	22
AH-64			8.4	43
	Mean horizontal velocity - All mishaps			
OH-58	29.2	85	31.6	178
UH-60	35.4	26	44.1	57
CH-47			41.1	22
AH-64			26.2	42

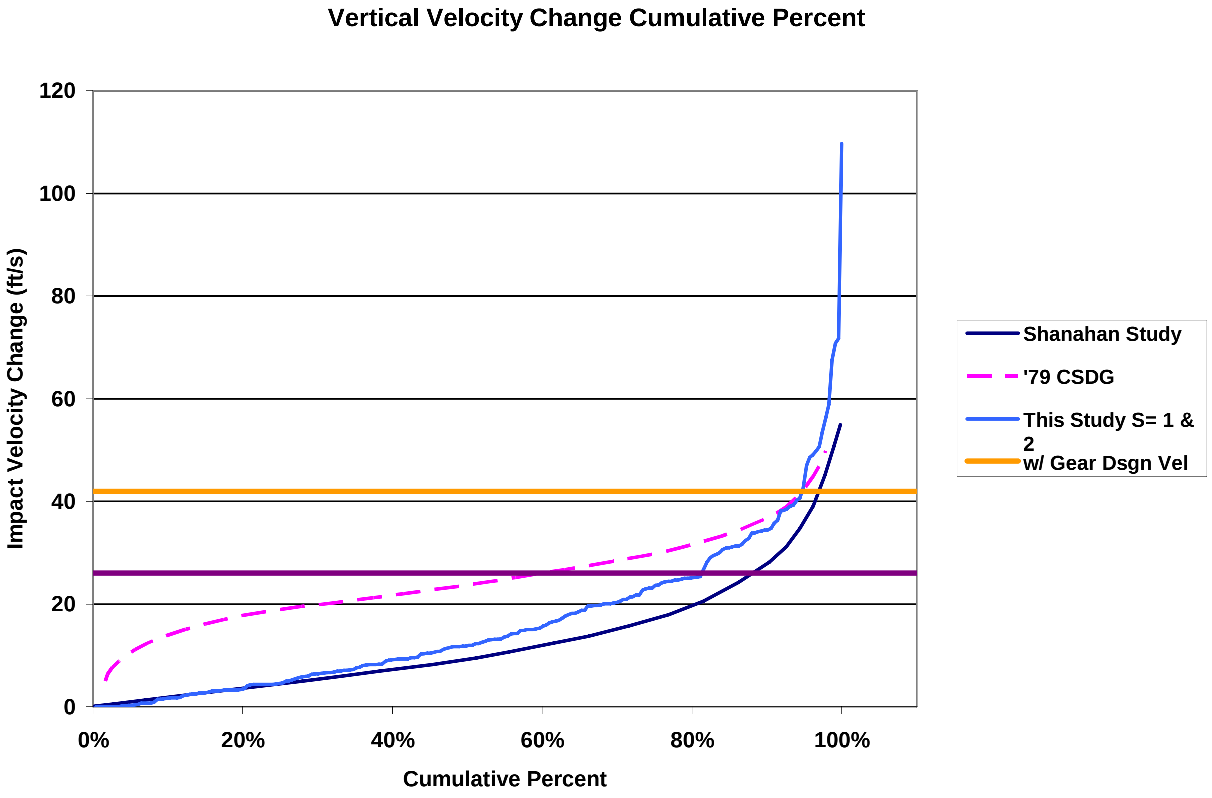

Figure 2-12. Comparison of vertical velocity cumulative percent curves for three studies (eRef. 1).

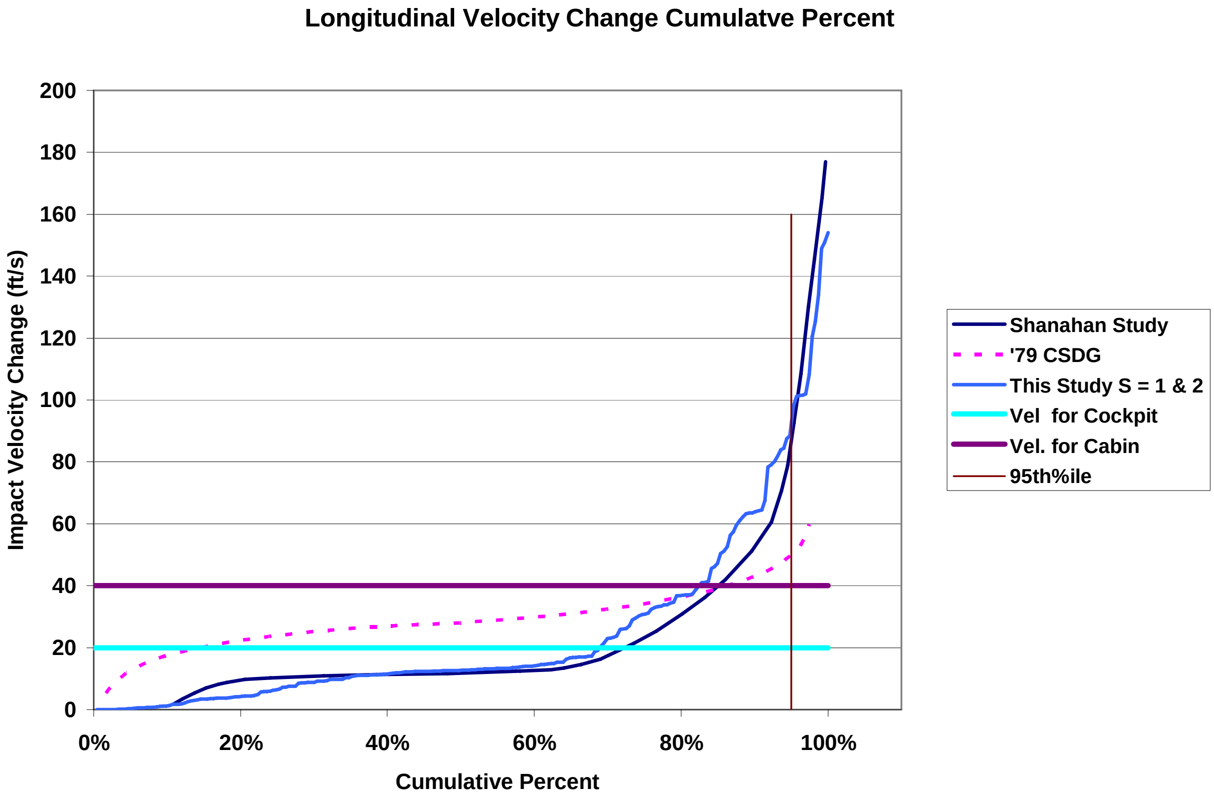

Figure 2-13. Comparison of longitudinal velocity cumulative percent curves for three studies (eRef. 2).

The two figures comparing the cumulative percent curves from the three studies show somewhat different velocity distributions, especially for the lower-percentile velocities. The current study appears to agree well with Shanahan's study, particularly for the longitudinal velocities. In the longitudinal velocities, the difference between the CSDG study and the later two studies may reflect the difference in mishap selection and analysis methodology. The vertical velocity curve matches the Shanahan curve well at low percentiles, but gradually diverges toward higher velocities with increasing percentiles. This difference may be partly attributable to the larger number of UH-60 and AH-64 mishaps in this study, as compared to Shanahan's study.

The relative numbers of non-survivable to survivable events included in the study may illuminate the differences. Table 2.7 indicates that for the OH-58, this study does indeed include a greater percentage of non-survivable accidents than the Shanahan study. However, the distribution for the UH-60 is very comparable between the two studies. Numbers for the other aircraft in both studies are provided for the reader's interest.

Table 2.7. Survivable, partially survivable, and non-survivable events - A comparison between studies

Aircraft (Study)	Total	Survivable Number (%)	Partially Survivable Number (%)	Non-survivable Number (%)
OH-58 (Shanahan)	85	67 (79)	10 (12)	8 (9)
OH-58 (This Study)	178[6]	122 (71)	21 (11)	33 (18)
UH-60 (Shanahan)	26	13 (50)	6 (23)	7 (27)
UH-60 (This Study)	60	28 (47)	15 (25)	17 (28)
AH-1 (Shanahan)	53	37 (70)	8 (15)	8 (15)
UH-1 (Shanahan)	133	104 (78)	16 (12)	13 (10)
CH-47 (This Study)	25	12 (48)	4 (16)	9 (36)
AH-64 (This Study)	44[7]	30 (70)	6 (14)	7 (16)

Two Axis Velocity Scatter Plots
The scatter charts of velocity are plotted after separating the impact velocity data into groups according to the survivability value assigned in the database (table: AIRCRAFT, variable: SURVIVABILITY). A chart is created for each pair of axes by plotting pairs of data points (one from each velocity for the same event) on the two graph axes. The charts shown in Figures 2-14 through 2-16 present the data for events with survivability ratings of 1 or 2; i.e., they are either survivable or partially survivable. Note that for the two plots involving vertical velocity, downward velocity was plotted as negative (the sign convention used in data collection is for the vertical downward velocity to be positive) to ensure that the downward velocity would appear downward on the chart. The author felt that this plotting convention would make the chart more intuitive to view. The data points are coded to show the identity of the aircraft.

The data in the Longitudinal - Vertical chart in Figure 2-14 reveal that high forward velocities can be survivable even in less-crashworthy designs such as the OH-58, particularly at low flight-path angles. This effect can be seen along the longitudinal velocity axis in Figure 2-14, as the mishaps with high longitudinal velocities tend to have low vertical velocities. Also remarkably, there are quite a few mishaps that have rearward velocity components. For the reader interested in 95th-percentile of survivability, ellipses representing these thresholds are plotted in the set of charts following this set. The reader will notice a heavy concentration of OH-58 longitudinal impact speeds around 15 ft/sec. The optimal autorotation combines forward speed with the vertical descent. For an aircraft with a high-inertia rotor system, it is not necessary, nor even desirable to execute a full flare for a zero velocity touch-down (Reference 11). This cluster of velocities is indicative of the pilots achieving close to the correct longitudinal velocity for a successful autorotation, but perhaps either the vertical velocity is too high or some other circumstance causes the landing to become a Class A or B mishap.

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[6] Two of the OH-58 events lack survivability ratings.
[7] One of the AH-64 events lacks a survivability rating.

The chart of Longitudinal - Lateral data in Figure 2-15 is plotted conventionally, with positive longitudinal velocity upward in the y axis; thus, forward appears as upward. This chart also suggests a bias for crashing toward the right with greater lateral velocities toward the right.

The scatter chart of Vertical - Lateral velocity in Figure 2-16 is plotted with the rightward velocity to the right (positive) and the downward velocity as negative (down on the plot). The bias of higher velocities to the right is not so clear in this chart perhaps because the points are more tightly clustered and more difficult to differentiate.

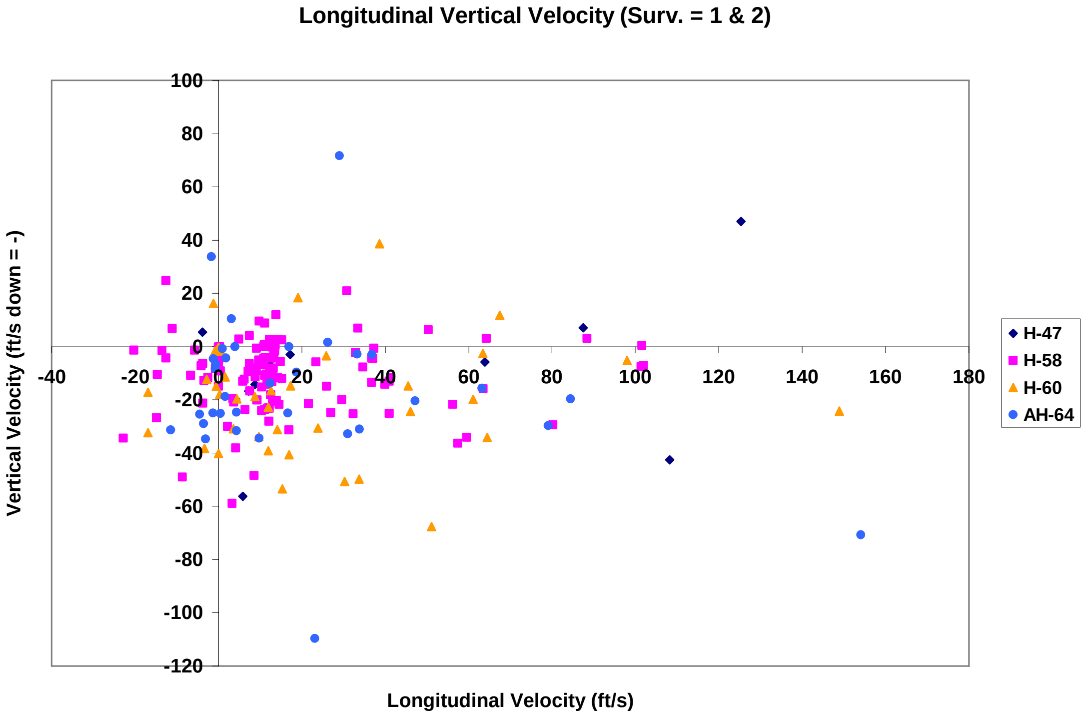

Figure 2-14. Longitudinal - vertical velocity scatter plot for survivability 1 & 2 (eRef. 5).

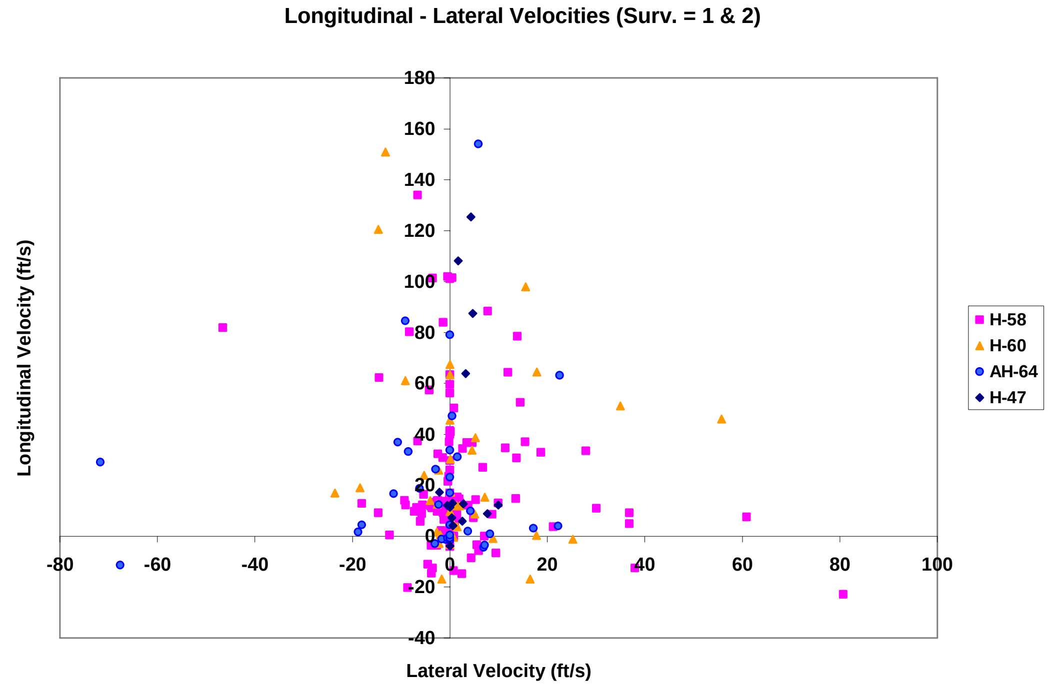

Figure 2-15. Longitudinal - lateral velocity scatter chart for survivability 1 & 2 (eRef. 6).

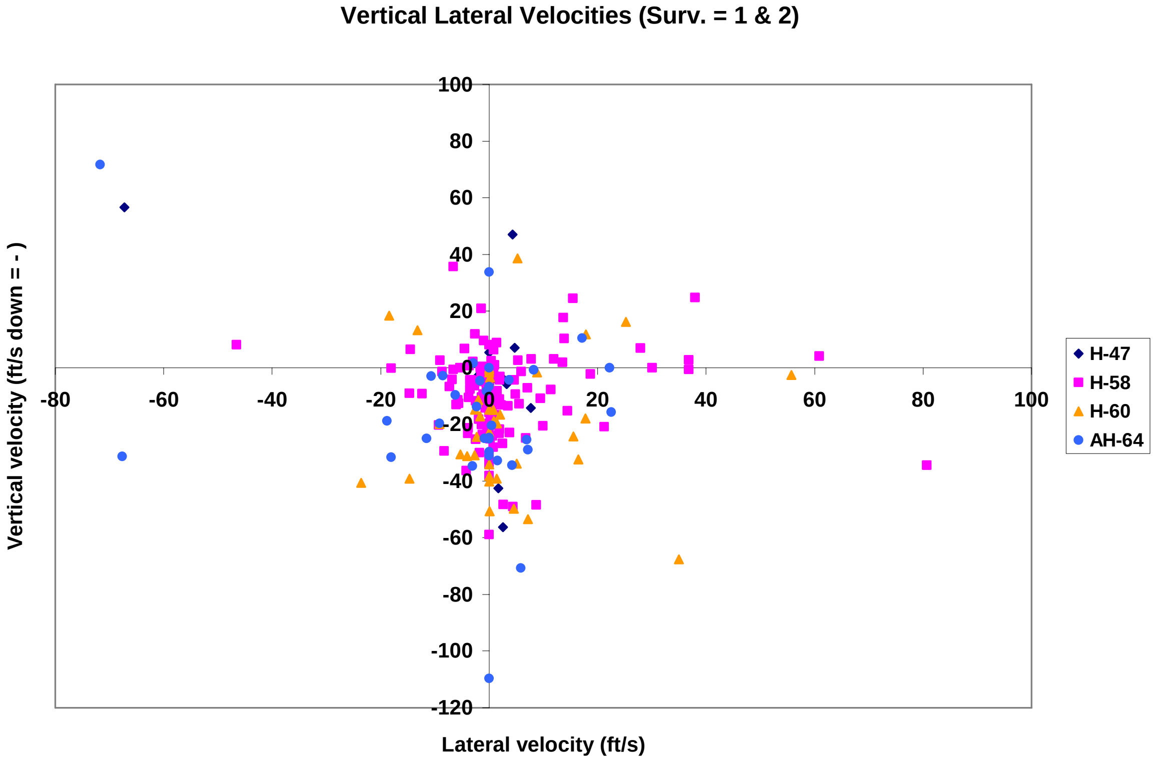

Figure 2-16. Vertical - lateral velocity scatter chart for survivability 1 & 2 (eRef. 7).

95th-Percentile Velocities

The 1979 CSDG presented elliptical velocity envelopes defined by the design velocities along the principle axes. The axis intercepts were connected by arcs established using the formula for an ellipse with the corresponding intercepts. These charts provide the designer concerned with crashworthiness with a tool to visualize the velocities at which crashes occur and to assist them in the setting design criteria for crashworthiness.

The next three plots (Figures 2-17 through 2-19) use the same data as was used in the two-axis scatter plots. The data were separated into positive and negative groups for each axis (the 0 values were divided using roughly the ratio corresponding to the non-0 data points). The 95th-percentile survivable velocity was determined for both positive and negative values of each major direction where sufficient data were available; generally, 10 data points were considered sufficient. The actual 95th-percentile value was interpolated from the two velocities on either side of 95 cumulative percent. This interpolation could be over a wide velocity increment, as the last three or four velocity values were often widely separated. The arc of an ellipse was created using these 95th-percentile velocities as the major and minor axis intercepts in the general equation for an ellipse. An elliptical arc was created for each quadrant where both velocities were available. The OH-58 was the only aircraft with sufficient data to place an arc in all four quadrants. Table 2.8 below shows the 95th-percentile values used in the plots. It is noteworthy that the OH-58 has a 95th-percentile vertical impact velocity of 35 ft/sec upright and nearly 25 ft/sec inverted.

Table 2.8. 95th-Percentile survivable velocities by axis and direction

Aircraft	**Forward**	**Rearward**	**Down**	**Up**	**Left**	**Right**
CH-47	113.0	-	48.0	-	-	8.6
OH-58	83.5	20.4	35.0	24.5	14.5	34.8
UH-60	107.0	-	53.6	-	-	33.8
AH-64	83.2	-	51.0	-	-	22.3

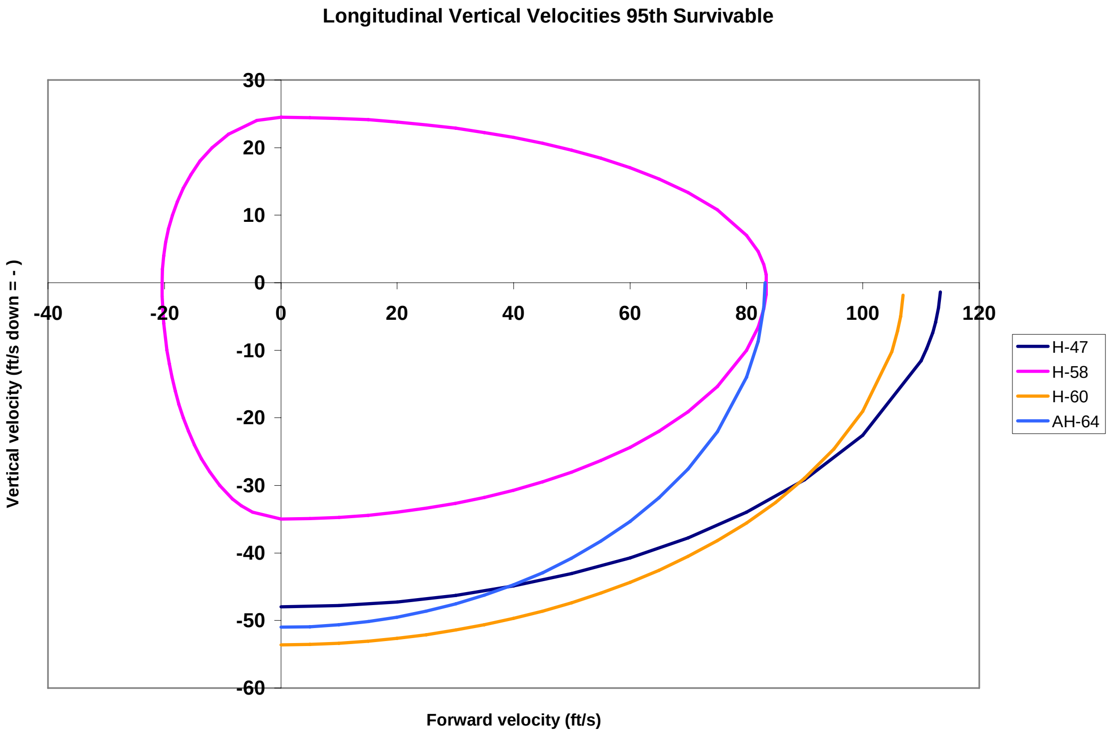

Figure 2-17. 95th-percentile survivable envelopes for longitudinal and vertical velocities (eRef. 8).

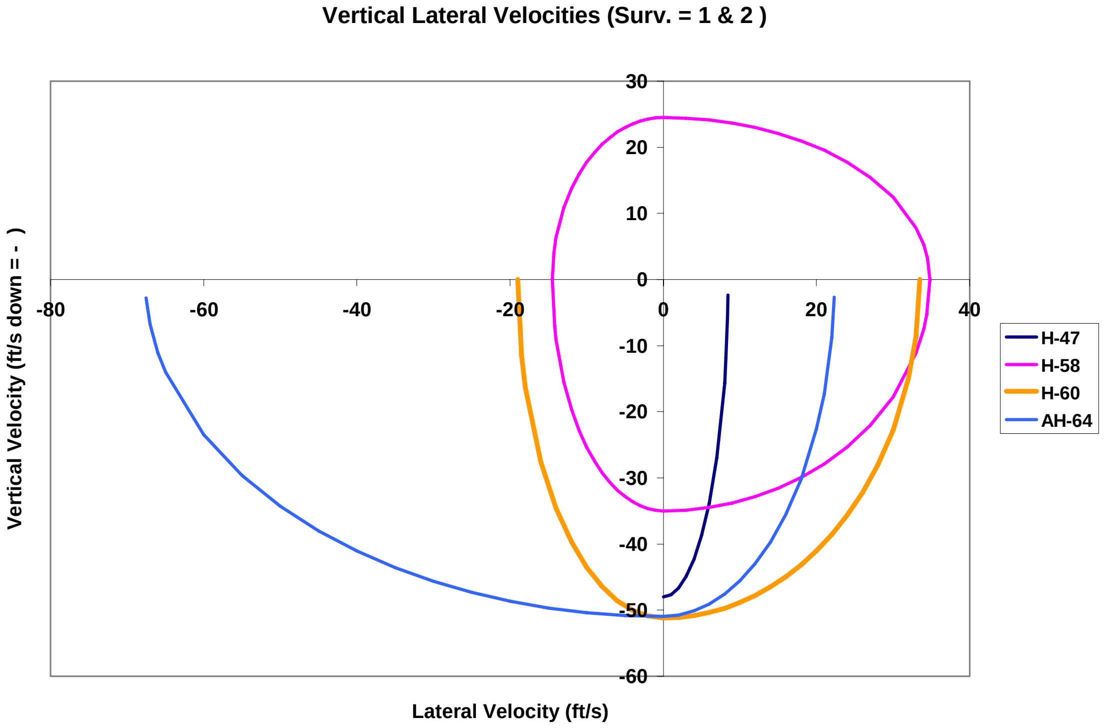

Figure 2-18. 95th-percentile survivable envelopes for vertical and lateral velocities (eRef. 9).

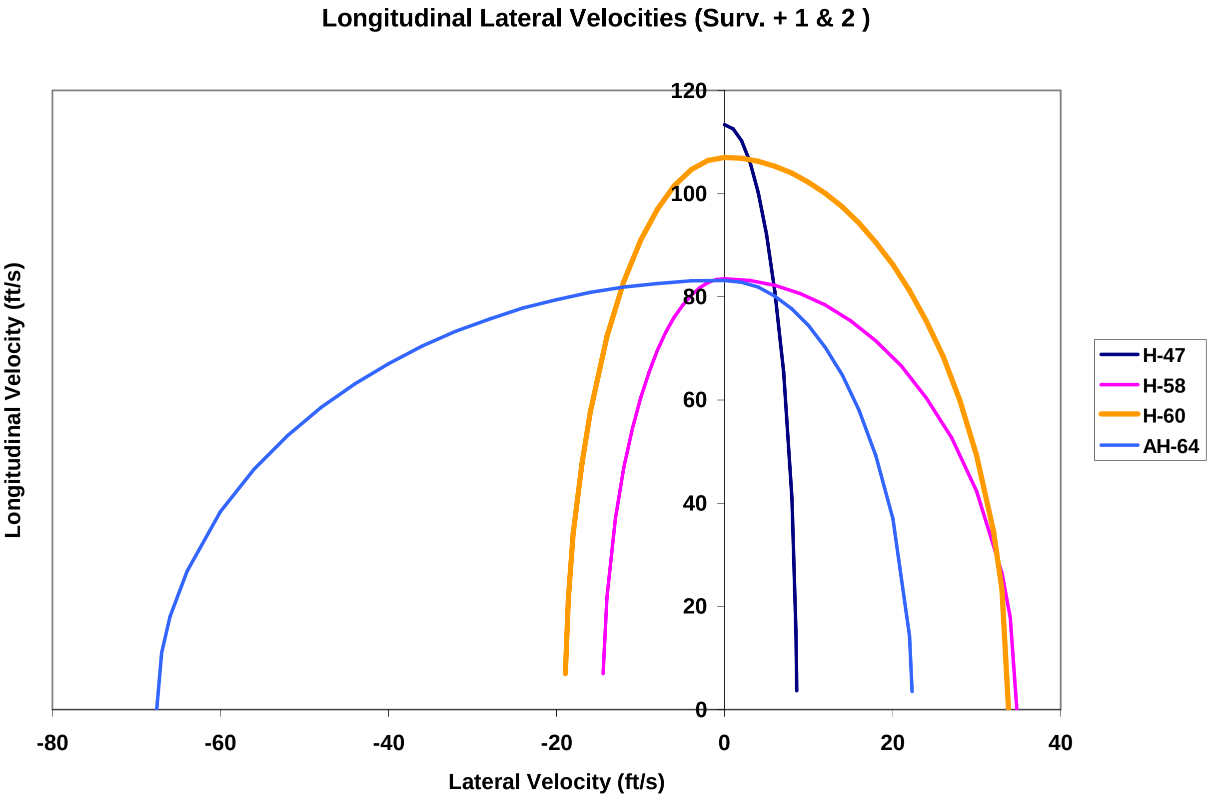

Figure 2-19. 95th-percentile survivable envelopes for longitudinal and lateral velocities (eRef. 10).

The 95th-percentile envelope would be expected to be reasonably symmetrical with respect to lateral velocity. The reason that the AH-64 has a very high 95th-percentile lateral velocity to port is that there are two significantly higher velocity events in that direction. Due to the limited number of data points, the 95th percentile falls between these two events. If these two events are ignored, the 95th-percentile envelope would be approximately symmetrical. However, these two events indicate that even lateral velocities as high as these are potentially survivable. The asymmetry in the OH-58 is based on 57 negative and 86 positive lateral points, suggesting that this asymmetry is not an artifact. The average lateral positive velocity for the OH-58 was 6.5 ft/sec, compared to -4.7 ft/sec for negative side. This discussion applies to both the vertical - lateral and the longitudinal - lateral plots, since the lateral data set is the same.

Table 2.9 compares the 95th-percentile velocities for the survivable mishaps to the 95th-percentile velocities for all mishaps. The 95th-percentile vertical velocity for all mishaps is about 45 pct higher than the survivable velocity; similarly, the longitudinal velocity is 50 pct higher. The lateral velocity for all mishaps is 132 pct higher than the 95th-percentile survivable lateral velocity. Table 2.10 lists the 95th-percentile velocities for each of four aircraft types and for each direction where sufficient data were available.

Table 2.9. 95th-Percentile velocity comparison - combined aircraft

Velocity Component	95th Survivable (ft/sec)	95th All (ft/sec)
Vertical	44.4	64.4
Longitudinal	92.0	138
Lateral	26.3	60.9

eRef. 1, 2, and 3.

Table 2.10. 95th-Percentile all mishap velocities by axis and direction

Aircraft	Forward	Rearward	Down	Up	Left	Right
CH-47	156	-	86.8	-	-	44.0
OH-58	138	-25.3	48.4	-68.1	-22.3	54.3
UH-60	151	-16.9	66.1	-159	-24.7	41.2
AH-64	143	-11.5	55.2	-	-70.5	31.3

Histograms of Angles at Impact

Again building on designer's familiarity with the CSDG, the following charts (Figures 2-20 through 2-25 and Tables 2.11 through 2.13) report the angle at impact as recorded in the database for all events included in the study. These are the angles used to transform the ground reference frame velocities into the aircraft reference frame. The first chart is a histogram including all four aircraft in a clustered bar chart and including the data from -180 deg to +180 deg. Note that at angles greater than 90 deg, the increment (or bin size) increases from 5 deg to 30 deg. The plot of all four aircraft combined into a single chart is presented as a stacked bar chart rather than another set of parallel bars on the single-aircraft clustered bar chart. Pitch is presented first, followed by roll and yaw. Because so many mishaps occur near the 0 angle, a table of values is presented for 10 deg on either side of 0. The stacked bar charts of all aircraft combined demonstrate the dominance of the OH-58 data in the combined aircraft charts.

As noted at the head of this section on angle at impact, this study has included the angle at impact for all events, rather than only the survivable events, as in the 1979 CSDG. Despite this difference, the mishaps in this study continue to occur predominantly at the nominal attitude of the aircraft, i.e., with all three angles at impact are at or near 0. Including the 20 pct of non-survivable accidents only serves to broaden the distribution slightly and add several events at extreme angles, including inverted and rearward impacts. In the pitch angle, the trend from the previous studies of a bias toward impact with the nose above the horizontal continues in this study. The 1979 CSDG found the roll angle to be virtually symmetrical about 0, and this trend was found in the Shanahan study as well. However, this study shows a distinct bias for a roll to the right. The 1979 CSDG did not present a chart for yaw, but Shanahan's study showed a very small bias to the right; this study finds a distinct bias for yaw to the right.

Pitch Angle Charts

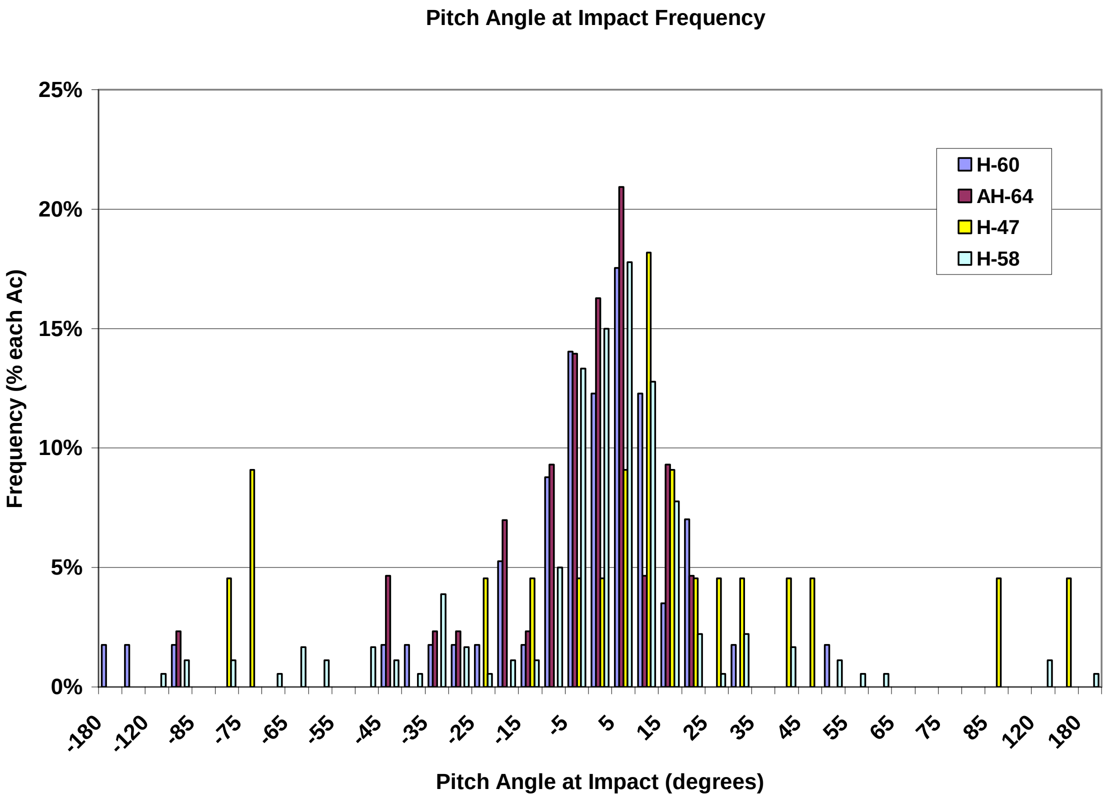

Figure 2-20. Pitch angle at impact for each aircraft type (eRef. 11).

Table 2.11. Cumulative pitch angle values between -10 and +10 deg for all events in the study (eRef. 11)

Pitch Angle Range	Events	% of All
-15 to -10	5	1.7
-10 to -5	18	6.0
-5 to 0	39	12.9
0 to +5	42	13.9
+5 to +10	53	17.5
+10 to +15	36	11.9
TOTAL	**193**	**63.9**

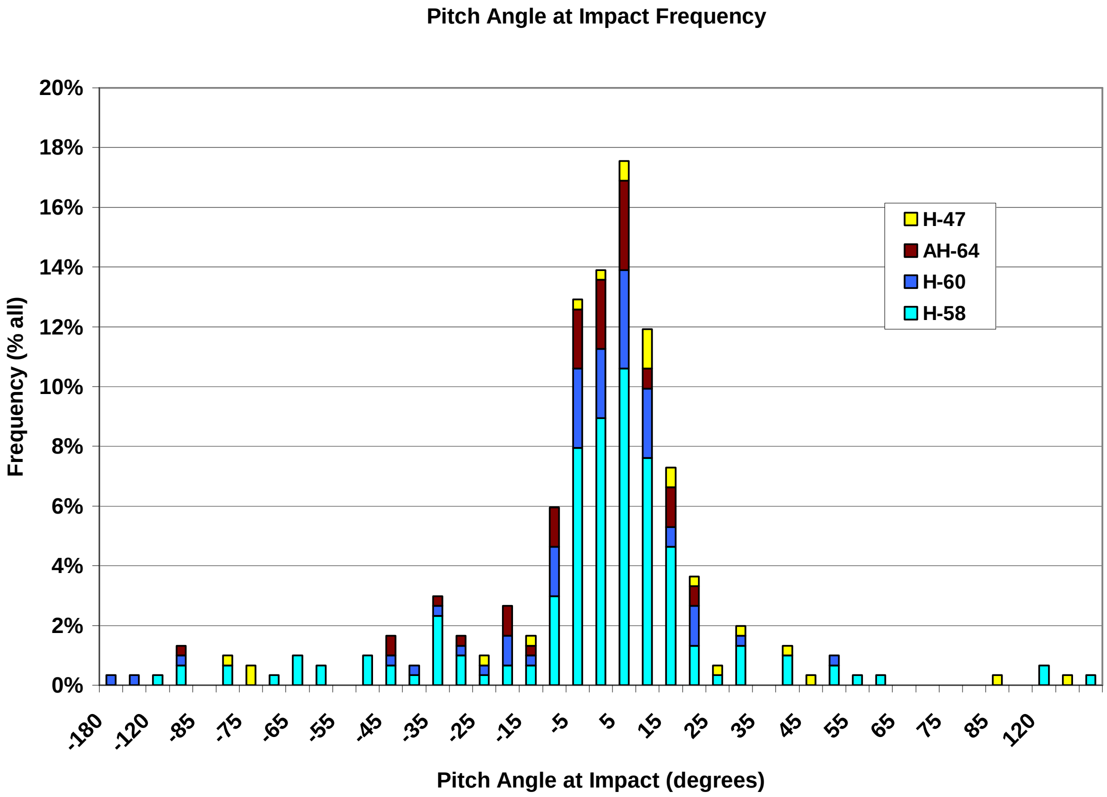

Figure 2-21. Pitch angle at impact for all four aircraft types combined (eRef. 11).

Roll Angle Charts

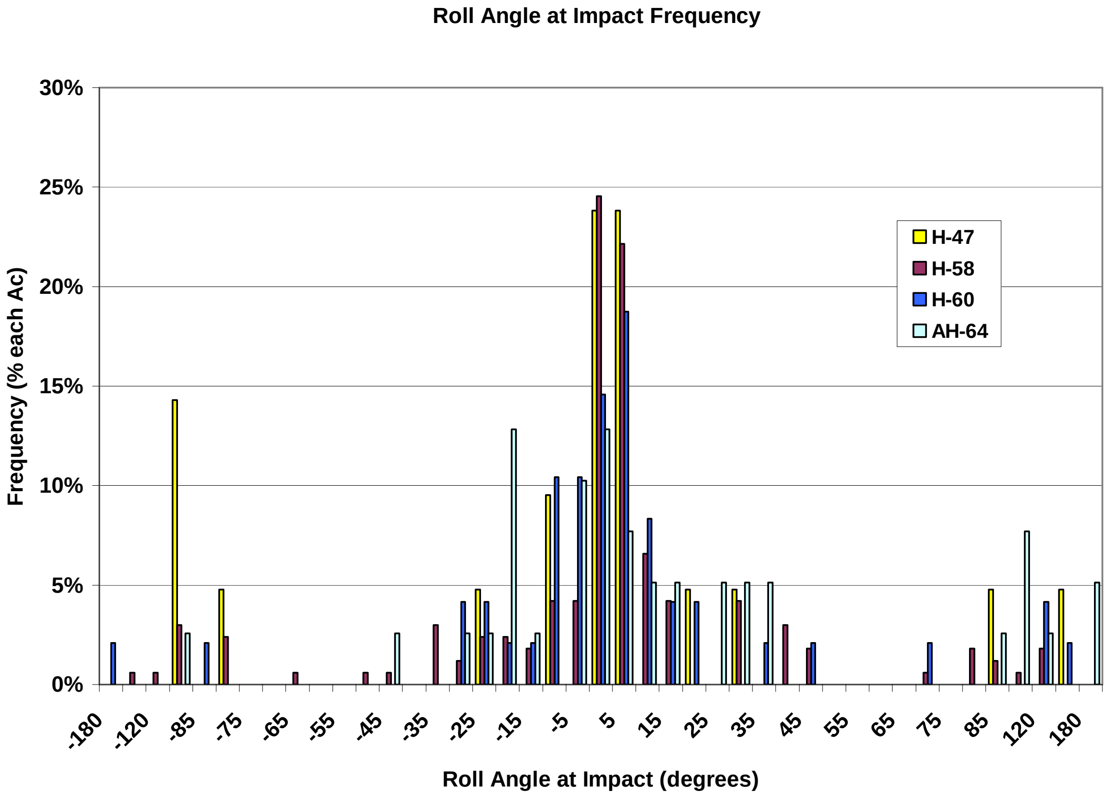

Figure 2-22. Roll angle at impact for each aircraft type (eRef. 12).

Table 2.12. Cumulative roll angle values between -10 and +10 deg for all events in the study (eRef. 12)

Roll Angle Range	Events	% of All
-15 to -10	5	1.8
-10 to -5	14	5.1
-5 to 0	16	5.8
0 to +5	58	21.1
+5 to +10	54	19.6
+10 to +15	17	6.2
TOTAL	**164**	**59.6**

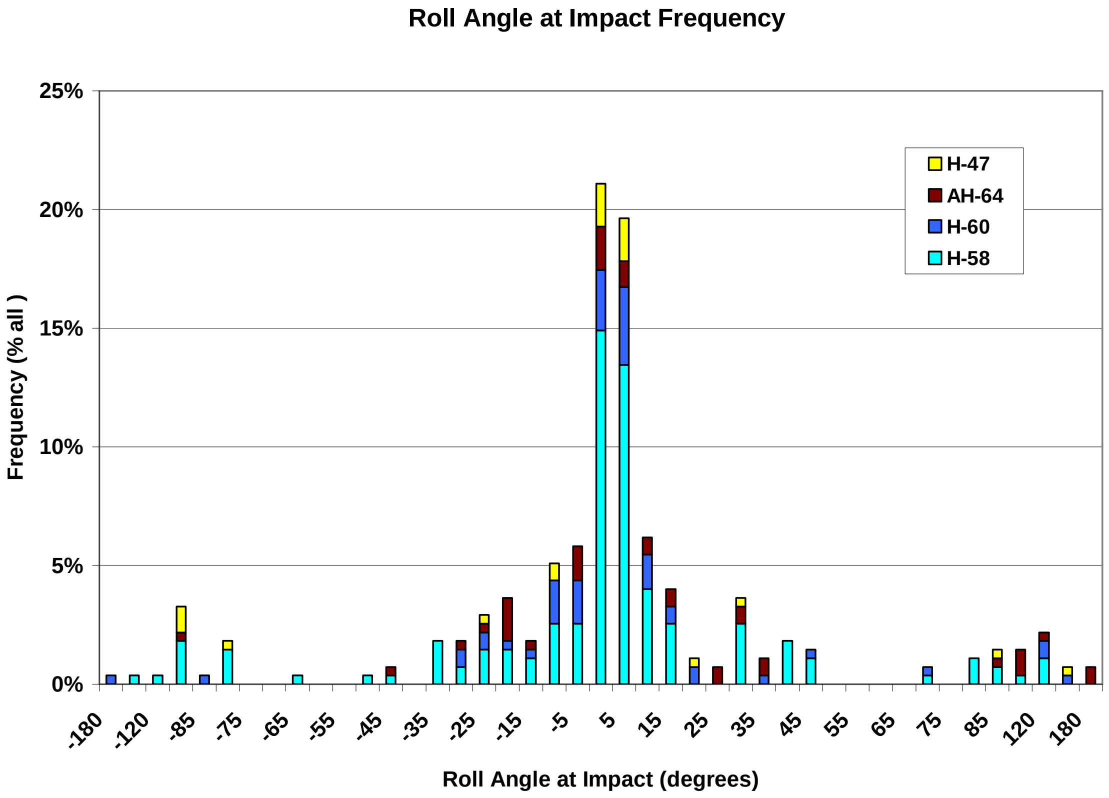

Figure 2-23. Roll angle at impact for all four aircraft types combined (eRef. 12).

Yaw Angle Charts

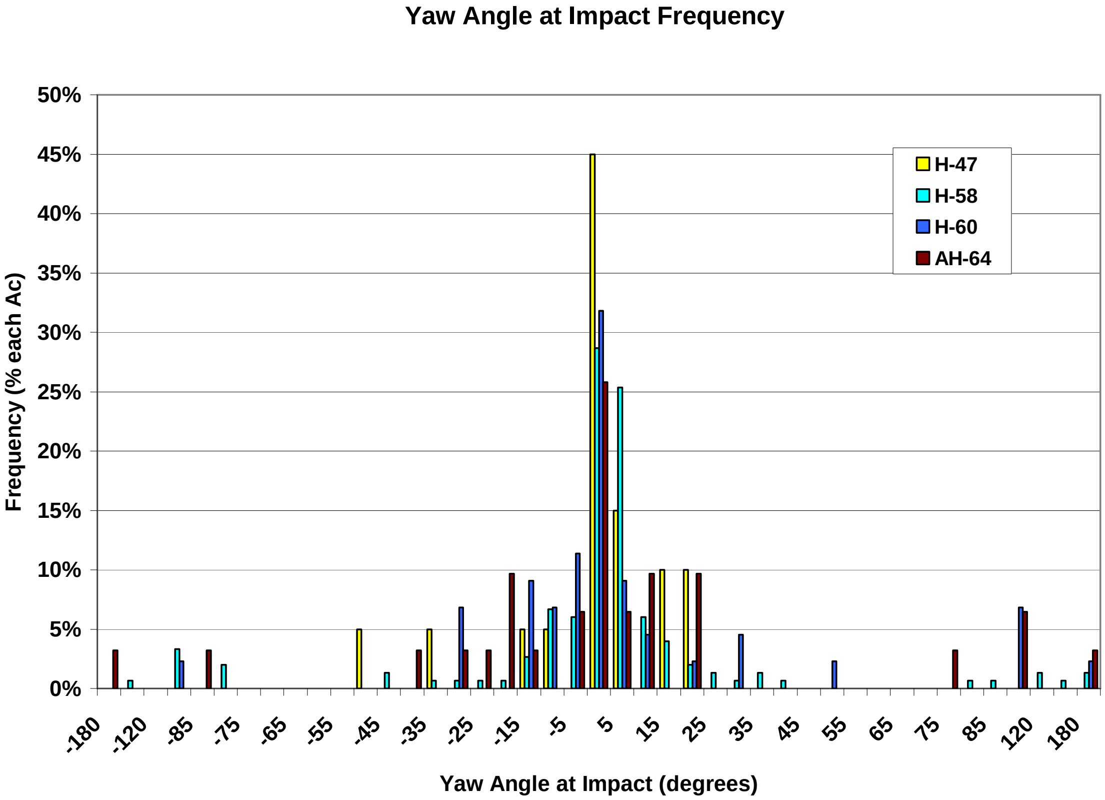

Figure 2-24. Yaw angle at impact for each aircraft type (eRef. 13).

Table 2.13. Cumulative yaw angle values between -10 and +10 deg for all events in the study (eRef. 13)

Yaw Angle Range	Events	% of All
-15 to -10	10	4.1
-10 to -5	14	5.7
-5 to 0	16	6.5
0 to +5	74	30.2
+5 to +10	47	19.2
+10 to +15	14	5.7
TOTAL	**175**	**71.4**

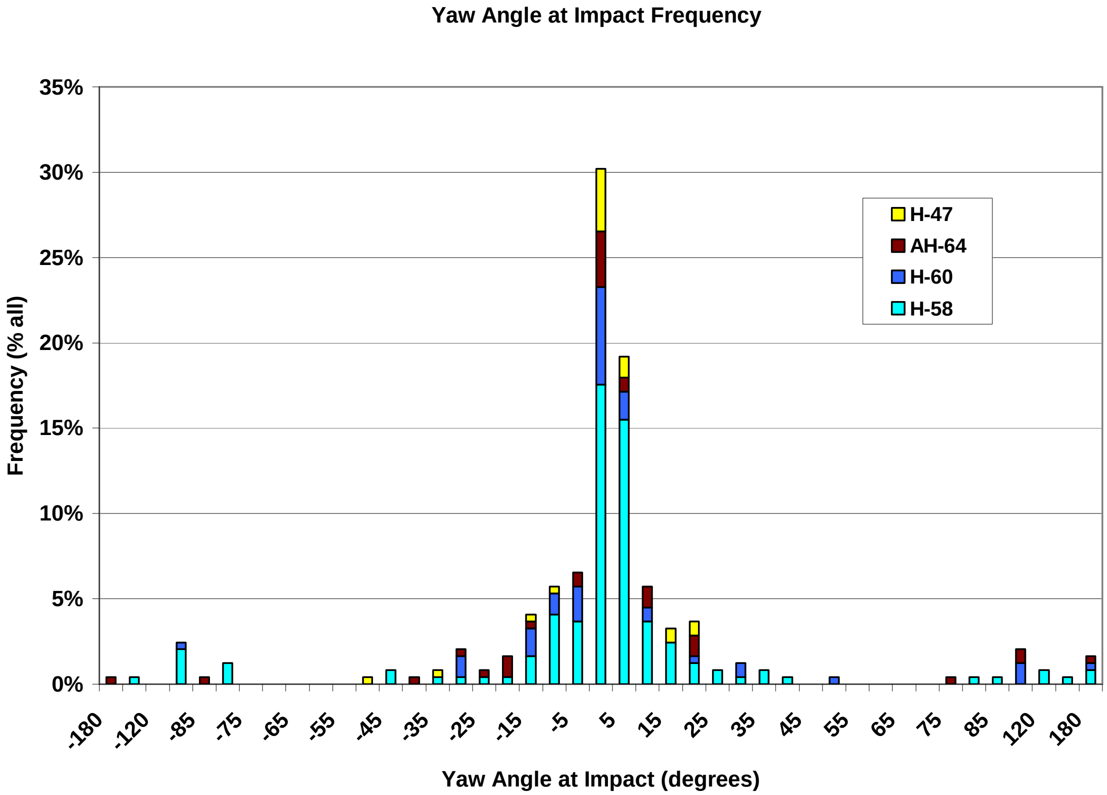

Figure 2-25. Yaw angle at impact for all four aircraft types combined (eRef. 13).

Impact Angle Cumulative Percent Charts

The following charts (Figures 2-26 through 2-28) present the angle information in the same cumulative percent format used for the velocity. The CSDG does not provide an historical reference, nor does it give a precedent for these charts. The charts plotting the impact angle against the cumulative percent include data from events at all survivability levels. The chart also includes a curve for all of the data combined into one set and a line representing the 95th percentile. The angle values were converted to absolute values before being placed in ascending order. For example, Figure 2-26 shows that for all aircraft combined, 80 pct of the events occurred with pitch angles less than 20 deg.

With the exception of the CH-47, the pitch angle on 70 pct or more mishaps is within 20 deg of the horizontal.

The roll angles show greater variability, with only 60 pct falling within 20 degrees of normal flight attitude. The AH-64 impacts at notably more divergent roll angles than the other aircraft.

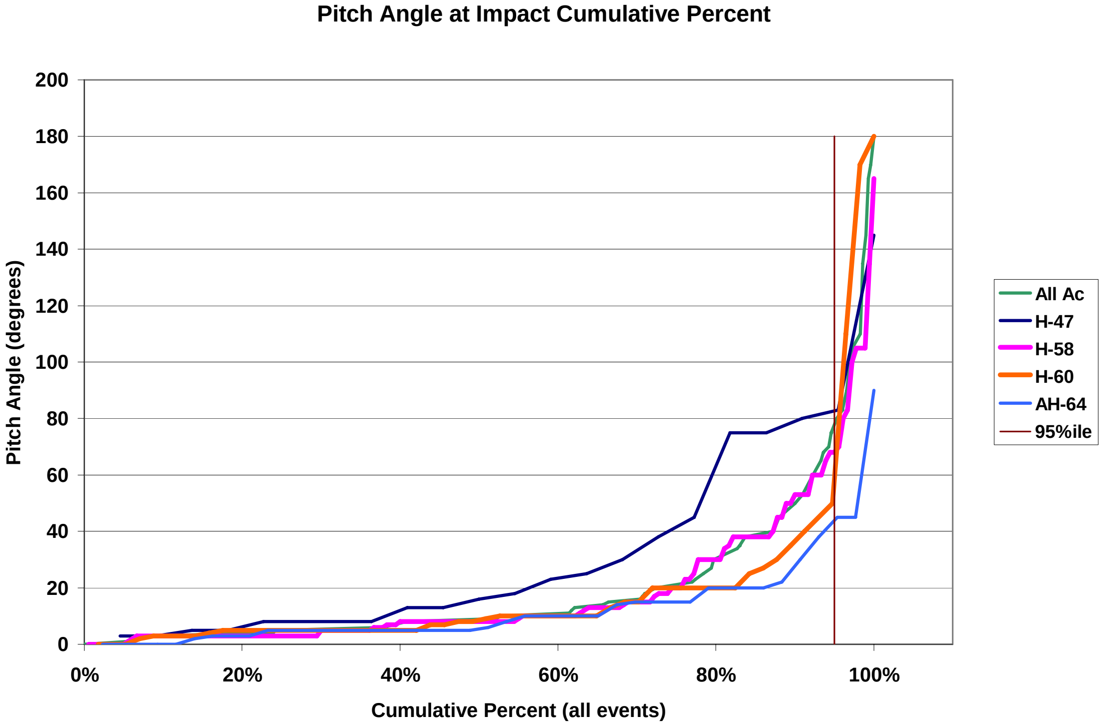

Figure 2-26. Cumulative pitch angle at impact (eRef. 14).

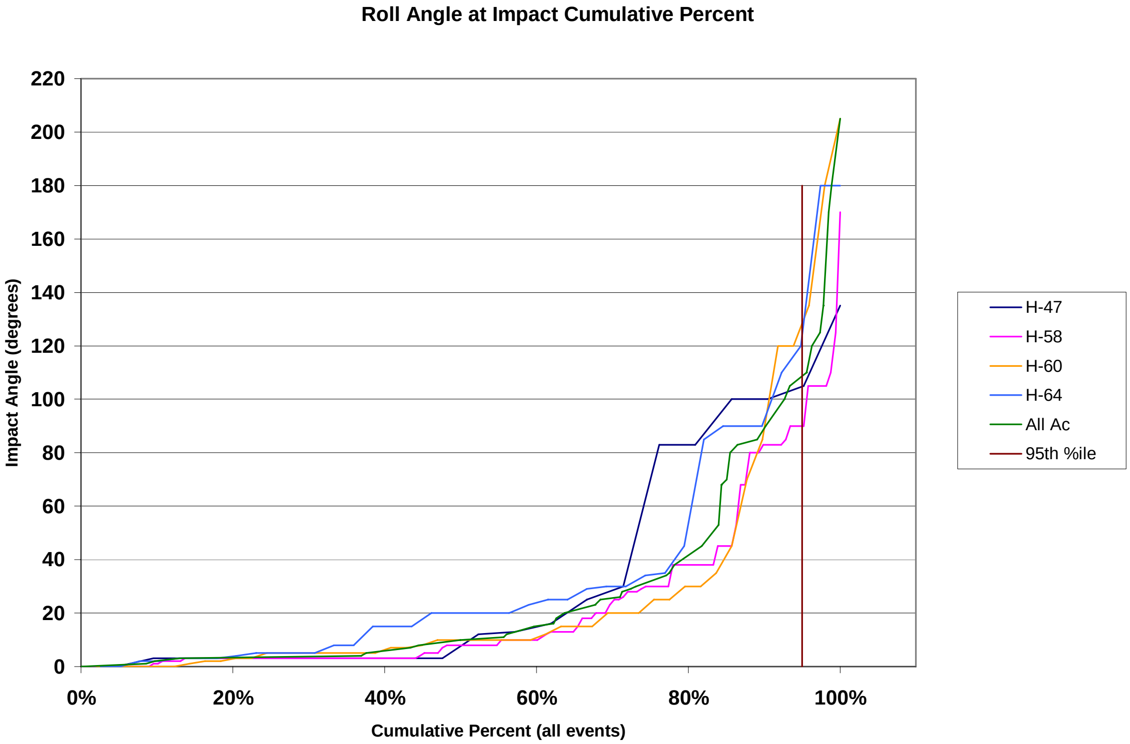

Figure 2-27. Cumulative roll angle at impact (eRef. 15).

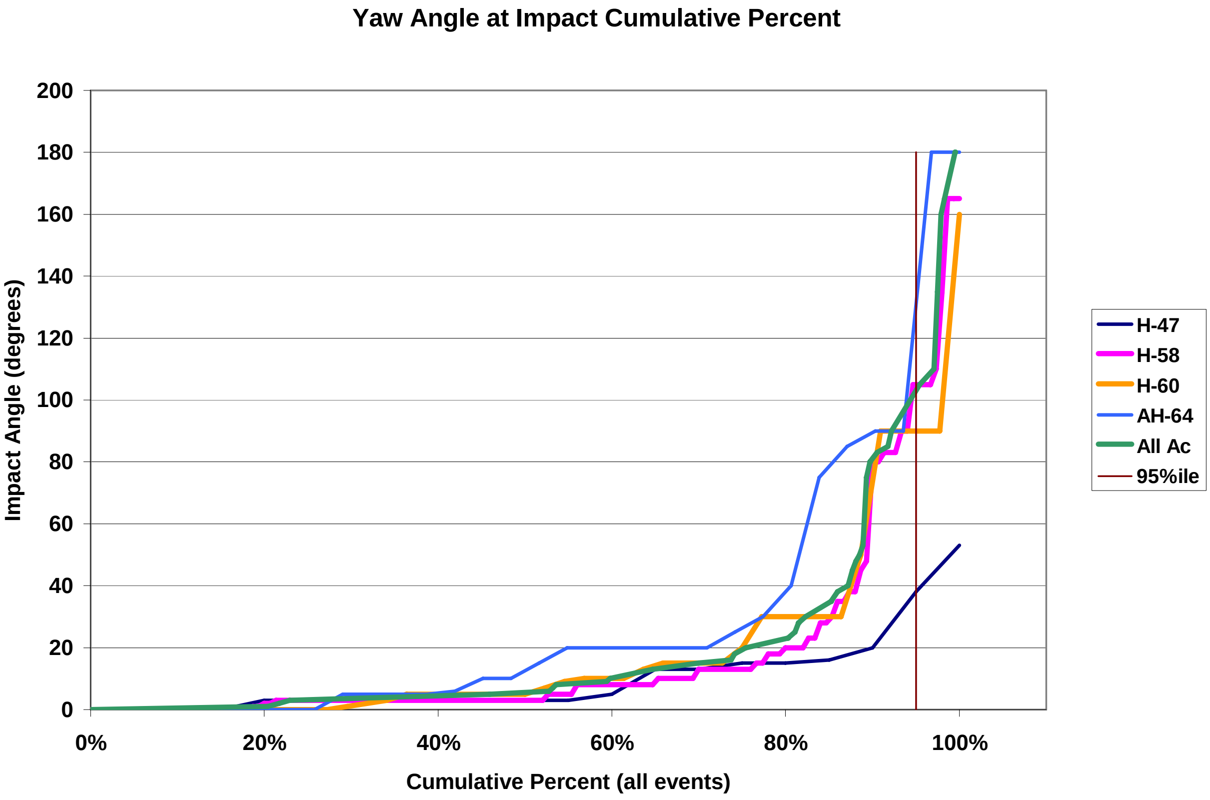

Figure 2-28. Cumulative yaw angle at impact (eRef. 16).

While all of the other aircraft have well over 70 pct of their yaw impact angles within 20 deg of the flight path, the AH-64 stands out with half of its mishaps at 20 deg yaw or greater.

Impact Angle Between Flight Path and Terrain

The following charts (Figures 2-29 through 2-32) present the information on the impact angle between the flight path and the terrain. The impact angle is defined as the included angle between the flight path and terrain. This angle represents the direction that the aircraft's center of gravity is moving relative to the impacted terrain irrespective of the aircraft's attitude. This angle is recorded in the database, as are the flight path angle and the slope angle. The flight path angle is the angle between the velocity of the aircraft's center of gravity and the horizontal. Thus, these two angles are related by the terrain angle; the impact angle is the algebraic sum of the flight path angle and the terrain angle. The terrain angle is the angle between the terrain and the horizontal measured in the vertical plane through the flight path. The quantity recorded in the database is the "Crash Site Grade". Unfortunately, the grade of the site is not necessarily the quantity of interest unless the aircraft crashes on the up-slope line. The block on the form includes a check box for level and one for slope. There is a space to record the slope, if it is not level. Thus, the database frequently has this datum blank rather than zero.

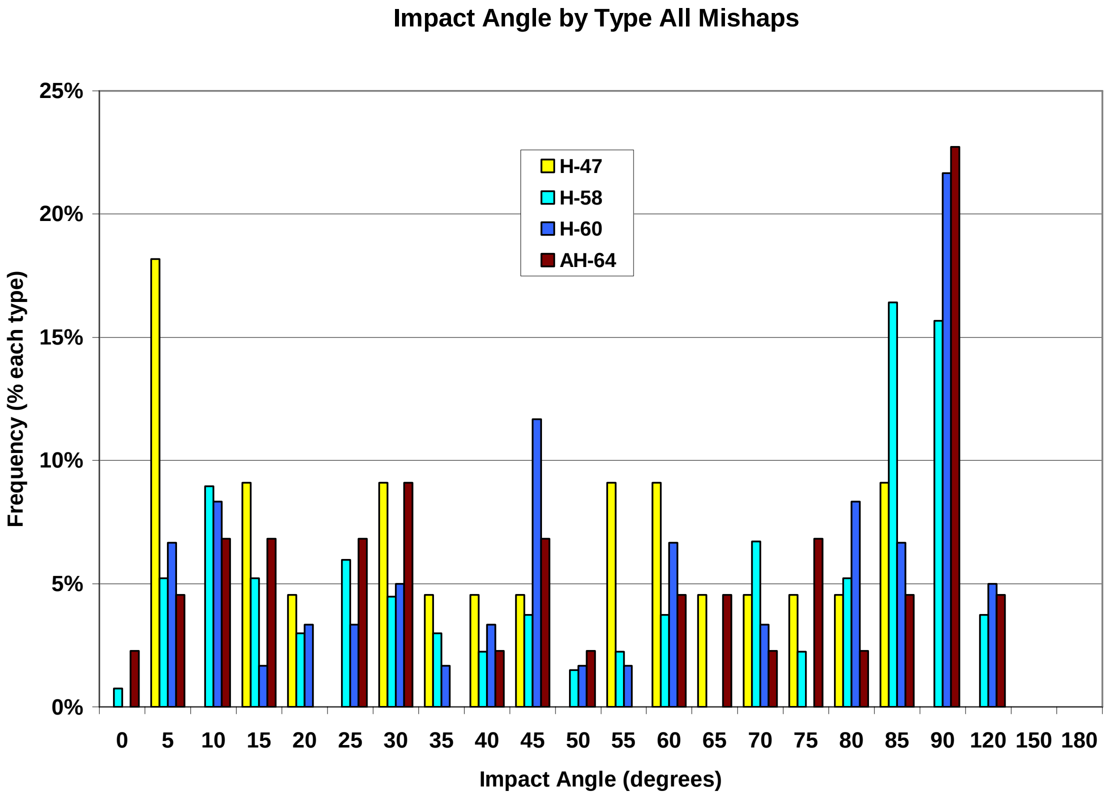

Figure 2-29. Aircraft impact angle by type including all mishaps (eRef 19).

A comparison of Figures 2-29 and 2-30 reinforces the idea that the survivable accidents tend to occur with the aircraft impacting near vertical or at a low angle allowing for a significant amount of “slide out”. In the survivable plot, the frequencies for the angles in between are lower than for the “all mishaps” curve.

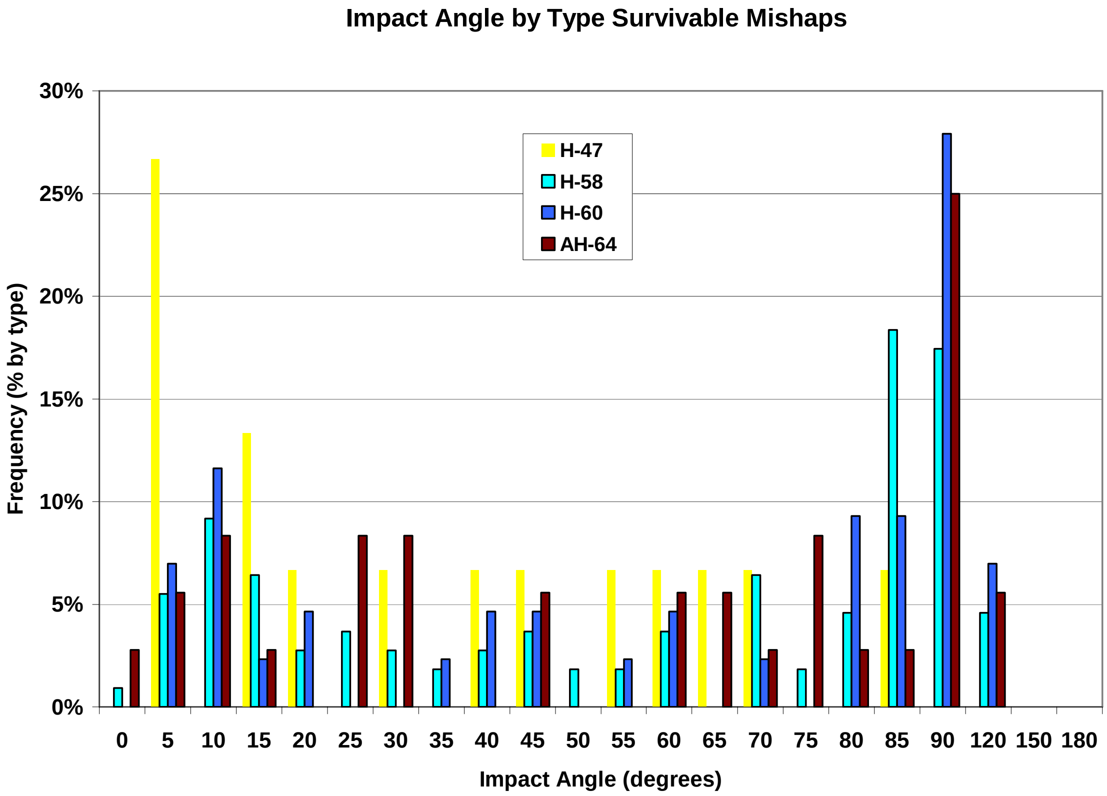

Figure 2-30. Aircraft impact angle by type including survivable (S= 1 & 2) mishaps (eRef 19).

Figure 2-31 shows how each aircraft contributes to the overall total of the impact angle distribution for all accidents, and Figure 2-32 presents similar information for the survivable mishaps. The stacked histograms reinforce that all of the three single-main-rotor aircraft tend to have a similar distribution. The data suggest that the H-47 has a lower tendency to crash in the pure vertical direction than the single rotor types. The stacked histograms show that H-47 also has a high frequency of near horizontal impacts.

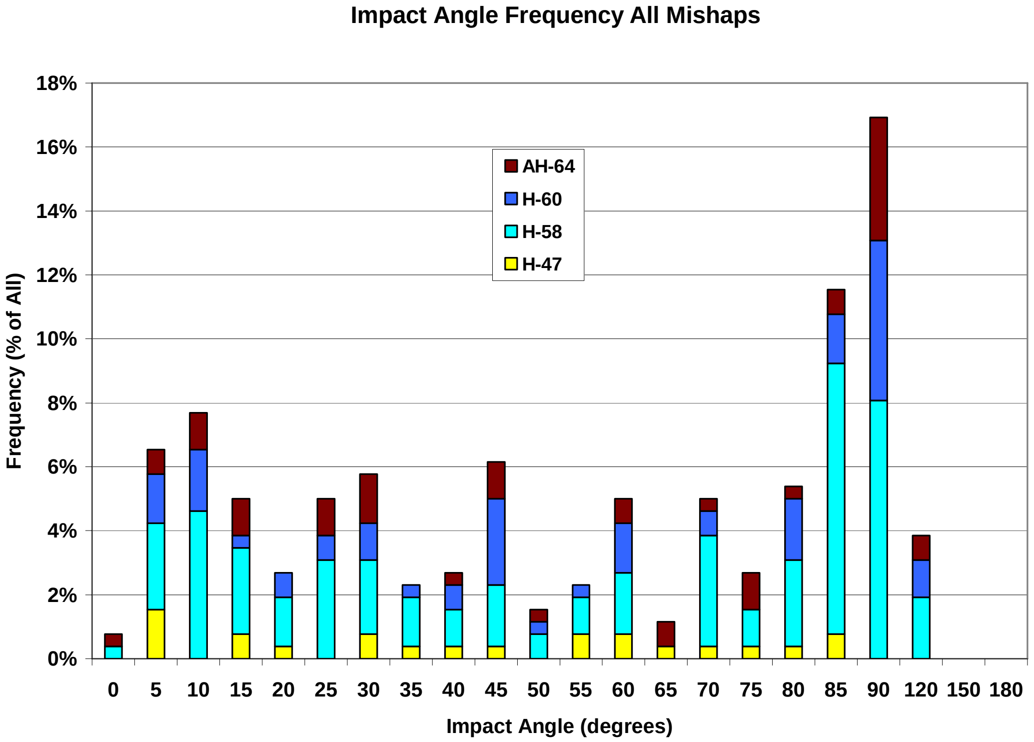

Figure 2-31. Frequency distribution of impact angles for all mishaps (eRef. 20).

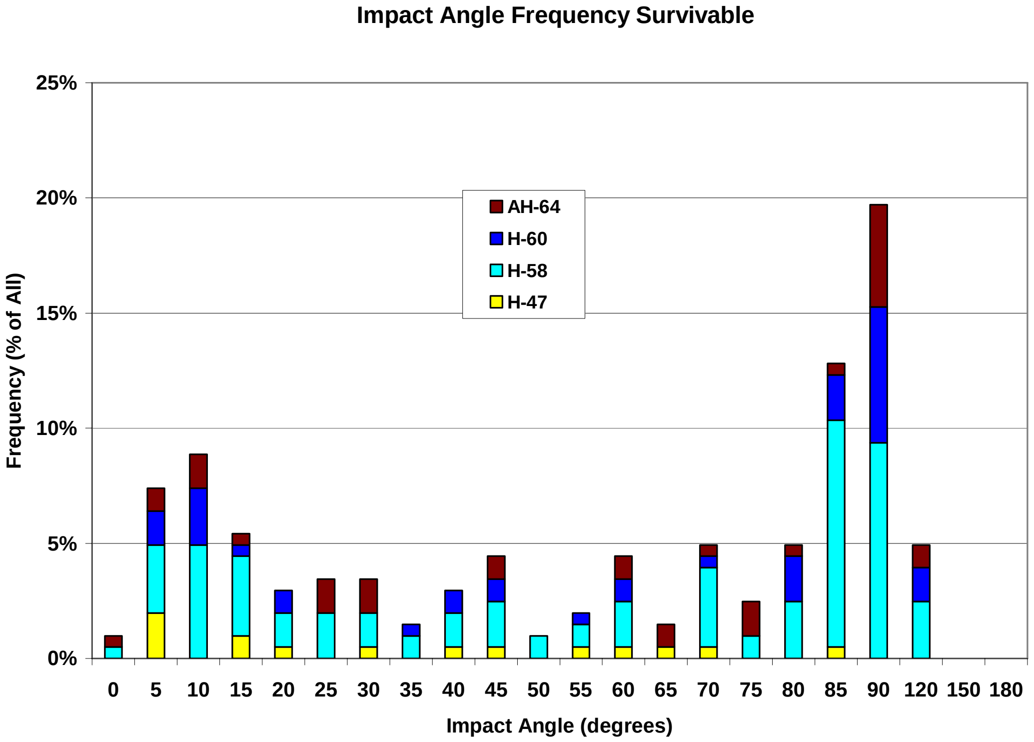

Figure 2-32. Frequency distribution of impact angles for all survivable mishaps (eRef. 20).

Operational Phase at the Outset of the Mishap

The Phase of Operation variable was revised in the database in the mid-1980s. The categories were changed dramatically; consequently, the data reported here is post-change. No attempt was made to go through the older data and convert it to the new definitions. The revised variable is called NEW_PHASE. For many, if not most, events, multiple values of NEW_PHASE are entered into the database; in some cases, this data covered virtually all of the phases of the mission including a value for "crash." In as much as the study selected only events that were crashes, use of this value was deemed redundant. Looking at the remaining values for each event, the analyst picked out one value as the most likely phase that the aircraft was in during the crash and selected a second value as the phase that most likely immediately preceded the crash. These values are reported in Tables 2.14 and 2.15 below.

Table 2.14. Occurrence of mission phases during the crash event (eRef. 17)

Phase	**at Crash**	**at Crash**	**at Crash**	**at Crash**		
	CH-47	**OH-58**	**UH-60**	**AH-64**	**Sum**	**Percent**
Emergency Autorotation (K)	1	21	5	5	32	23
Landing (M)	3	5	8	1	17	12
Hover OGE (Q)	0	5	1	10	16	11
Descent (I)	0	5	3	5	13	9
Low Level (N)	1	5	1	5	12	9
Cruise (G)	1	3	3	4	11	8
Approach (J)	1	4	5	1	11	8
Contour (O)	0	3	2	4	9	6
Hover IGE (E)	0	3	0	2	5	4
Training Autorotation (W)	0	5	0	0	5	4
Combat Maneuver (H)	0	2	0	1	3	2
NOE (P)	0	3	0	0	3	2
Climb from T.O. (F)	1	1	0	0	2	1
Go-Around (L)	0	0	1	1	2	1
Turning (2)	0	0	0	0	0	0
Undetermined (U)	0	0	0	0	0	0
Power Recovery (V)	0	0	0	0	0	0
Formation (X)	0	0	0	0	0	0

Table 2.15. Occurrence of mission phases just prior to the crash event (eRef. 17)

Phase	Prior CH-47	Prior OH-58	Prior UH-60	Prior AH-64	Sum	Percent
Cruise (G)	0	8	1	3	12	15
Descent (I)	0	4	4	2	10	12
Approach (J)	0	5	4	1	10	12
Hover OGE (Q)	0	3	1	3	7	9
Formation (X)	0	0	4	3	7	9
Contour (O)	0	3	2	0	5	6
Combat Maneuver (H)	0	1	1	2	4	5
Emergency Autorotation (K)	0	0	3	1	4	5
Low Level (N)	0	2	1	1	4	5
NOE (P)	0	2	0	2	4	5
Hover IGE (E)	0	1	2	0	3	4
Training Autorotation (W)	0	2	0	1	3	4
Go-around (L)	0	0	2	0	2	2
Power Recovery (V)	0	2	0	0	2	2
Turning (2)	0	1	0	0	1	1
Climb from T.O. (F)	0	1	0	0	1	1
Landing (M)	0	1	0	0	1	1
Undetermined (U)	0	1	0	0	1	1

As might be anticipated, the most frequent phase recorded during the crash is an emergency autorotation. Helicopter aircrews often have significant time to respond to emergencies. Survivable emergencies may be precipitated by events as minor as unusual noises in the drivetrain to events as major as impacting wires during forward flight. The phase prior to the emergency does not suggest a strong trend, although hover and formation flying appear to more dangerous than might be anticipated. The only category covering training is “training autorotation”; however, reading the mishap summaries, one sees far more reference to training activities than the 4 pct reflected in the training autorotation phase. There were at least as many mishaps precipitated by practicing simulated engine failures. Neither the Shanahan study nor the 1979 CSDG have comparable tables for comparison with this data. The 1989 CSDG did not address this aspect of crashworthiness either.

Terrain descriptors appear in three places in the database, all of which are to some extent germane to the outcome of a crash. The data table TERRAIN_GENERAL contains a variable called CHARACTERISTICS, the table TERRAIN_SURFACE contains a variable called SURFACE, and the table TERRAIN_OBSTACLE contains a variable called OBSTACLE. In as much as each of these parameters describes the “terrain” in a slightly different way, the analyst has chosen to combine the results of all three variables into a single table describing terrain (See Table 2.16).

Table 2.16. Impact surface descriptors including all mishaps (eRef. 18)

Surface Characteristics	CH-47	OH-58	UH-60	AH-64	Sum
Flat (8)	5	47	19	16	87
Rolling (11)	4	46	17	15	82
Mountains (14)	7	32	11	7	57
Desert (13)	3	20	6	1	30
Water (9)	2	11	3	0	16
Surface					
Sod (2)	13	128	41	35	217
Prepared (1)	1	14	6	1	22
Soggy (3)	2	9	4	3	18
Water (16)	2	8	3	0	13
Snow (15)	0	4	3	1	8
Ice (4)	1	0	0	0	1
Surface Obstacle					
Trees (05)	9	58	30	24	121
Rocks / Boulders (06)	3	24	3	2	32
Wires (18)	0	18	3	5	26
Other (98)	6	12	5	1	24
Buildings (10)	0	4	1	0	5
Stumps (17)	0	0	0	1	1
Number of Events	**25**	**189**	**60**	**44**	**318**

Many of the events reported multiple descriptors in each of the categories. For example, an event might be reported as occurring in “desert” and “mountains” or on “soggy” and “sod.” In organizing the data, the analyst kept track of two of these parameters each for Surface and for Surface Obstacles, but only one set of these is reported in Table 2-16. Stumps frequently appeared together with trees; trees were given precedence as the more severe obstacle. Likewise, rocks / boulders also appeared with trees, and again trees were given precedence. The number appearing in parentheses after the descriptor is the database code for that descriptor.

The reader is cautioned that these statistics are from an Army incident database and as such reflect the activities and mission profiles of Army aircraft. Undoubtedly, a similar study based on a U.S. Navy database, even including U.S. Marine aircraft, will show a different distribution of velocities and angles at impact. Just as obviously, water will be the impact surface in a far larger fraction of the events. Quantifying impact characteristics for the Navy has the additional complication of high sea states where the water at the instant of impact can be at a wide range of angles (waves) relative to the horizon.

Several observations from these tables are worth noting. Slightly over 68 pct of the impacts occurred into sod; thus, efforts to prevent plowing, which would reduce deceleration forces and chances of rollovers, continue to be merited. The frequency of impacts on sod has actually increased compared to the 1979 CSDG, which reported 43 pct on sod. Conversely, the frequency of impacts onto prepared surfaces remains low at 7 pct, which is nearly identical to the 1979 CSDG. Trees were reported as obstacles in 36 pct of impact sites. Water was reported as the surface for 4 pct of the mishaps; even including all of the “soggy” surfaces, water only constitutes 9 pct of the Army impact sites, at a maximum. For comparison, the 1979 CSDG listed “bog” at 6 pct, water at 2 pct, and snow or ice at 1 pct each.

Design and Mission Factor Investigation

In the previous section, the information collected from the database was presented in several charts. The chart designs were chosen for easy comparison to prior crashworthiness studies. Several new charts were also created. The objective of the following section is to analyze the information collected from the database and presented in those charts. Analyses have been performed using statistical tools that will indicate the validity of the conclusions drawn. Ultimately, the desire is either to confirm that the existing design rationale continues to be valid or to identify new trends and relationships within the data.

Most of the analysis has been carried out on the velocities along the three primary aircraft axes and on the three attitude angles at impact, because this information is expected to be most useful to the designers. Only limited analysis has been conducted on the original speed variables of GROUND_SPEED and VERTICAL-SPEED.

The reader is reminded of several considerations regarding the data. The OH-58A-C and the OH-58D datasets are subsets of the OH-58 data. The reason for differentiating between the OH-58A-C models and the OH-58D model is that the D model has a revised rotor system design. The OH-58D rotor system has both reduced rotor inertia and reduced rotor disk area (see Table 3.5). At the outset of the study, the analysts anticipated that this difference in rotor system design on an otherwise similar airframe might lead to a difference in the impact kinematics, particularly in the vertical velocity. The OH-58, with two different rotor system designs, represents a rare instance in this type of work where a single variable has been changed. The OH-58 data are divided into two sets; thus, in this section, the five aircraft types analyzed are the OH-58A-C, OH-58D, H-60, H-47, and AH-64.

Most of the following analysis reports values based on datasets including Survivability 1 and 2; i.e., survivable or partially survivable. Analyses including non-survivable mishaps will be identified as such. Table 2.6 presents the number and percent of non-survivable mishaps for each aircraft type in this and previous studies.

Hypothesis testing was used to identify significant differences among the five aircraft types on the impact velocity and impact angle variables. The most powerful test to determine differences in the central values of the distribution is the “t-test”, a parametric test that requires that the two samples be approximately normally distributed. The original datasets were generally not normal, but they were close enough to be able to use the t-test comfortably. In some cases, the analysts preferred to split the data into positive and negative groups, or take the absolute values of the actual data points. When the datasets were split or were made absolute, the departure from normal became much more severe. The datasets were all “light-tailed” in comparison to the normal distribution, meaning that the extreme portion of the distribution spreads out less far relative to the width of the center of the distribution. Use of the parametric t-test on data that follows a “light-tailed” distribution can lead to an incorrectly small p-value, which will tend to detect a difference in means when, in fact, no difference exists.

To counteract this “light-tail” effect, a non-parametric test called the “one-sign test” was used. The one-sign test is a non-parametric method that does not require an assumption about the distribution. Instead of calculating confidence intervals based on the mean and standard deviation of the dataset, the one-sign test uses the median. The two-sample variant of the one-sign test is the Mann-Whitney comparison. From the Mann-Whitney tests, a point estimate of the difference between the two samples with an associated confidence interval can be determined, as well as a p-value that indicates whether the difference is statistically significant.

Thus, in the following analysis for cases where the normality violations are less severe, conclusions may be drawn from the mean. However, where the non-normality is more severe, drawing a conclusion regarding the median is more justified. Although the value of the median may be less severely affected by extreme values, the median is generally regarded as less useful for inferring or predicting future values. In the following sections, conclusions will be presented that refer to either means or medians. As they are the stronger parameter, means are presented where valid. Any differences that are significant at a confidence level of 90 pct or greater are identified in the following discussions.

VERTICAL_SPEED (algebraic)

The VERTICAL_SPEED is stored in the database as two values, the magnitude of the speed and the direction (up or down). These two parameters were combined into a single algebraic value with positive being downward velocity; thus, here the mean includes negative values. Statistical analysis of the means (including all survivability levels) revealed that the OH-58D impacted with lower mean vertical velocity than the other three aircraft types (See Table 3.1). All three of these differences proved significant at greater than 90 pct. Likewise, the OH-58A-C impacted at significantly lower vertical speeds than the UH-60. The differences in vertical speeds between the other three aircraft were not significant. The difference between the OH-58A-C models and the OH-58D model was also not statistically significant.

Table 3.1. Comparison between aircraft types of mean vertical impact speeds (All mishaps)

Aircraft	Mean Speed (ft/sec)	Speed Standard Deviation	Speed Difference (ft/sec)	Significance level (%)
OH-58D	16.67	12.66	-	-
UH-60	35.76	32.34	19.09	99.9
AH-64	26.89	30.75	10.22	94.8
CH-47	33.20	45.44	16.53	91.1
OH-58A-C	19.23	24.77	-	-
UH-60	35.76	32.34	16.53	99.9

Vertical Impact Velocity

The vertical impact velocity is the velocity along the vertical axis of the aircraft, and the positive direction is downward by convention. This parameter is highly relevant to the designer, because it influences design issues, including landing gear energy-absorption capacity, airframe vertical structural strength, sub-floor energy-absorption capacity, and energy-absorbing seat stroke. In reviewing the data for this parameter, the analysts found a substantial number of mishaps with negative (i.e., upward) impact velocities. Because upward and downward vertical impact velocities have very different implications for the designer, the analysts elected to study positive and negative vertical velocity separately. Table 3.2 gives the mean values for each aircraft together with the mean VERTICAL_SPEED (earth coordinate system) values from the previous section. The second column in Table 3.2 is the mean for the velocity before separation into positive and negative groups. It should be noted that the Vertical Velocity analysis includes Survivability 1 and 2 only.

Table 3.2. Mean values of vertical velocities by aircraft (N mishaps)

Aircraft	Mean Vert. V. S=1 & 2 (cases) (ft/sec)	Mean (+) Vert. V. S=1 & 2 (cases) (ft/sec)	Mean (-) Vert. V. S=1 & 2 (cases) (ft/sec)	Mean Vert. Speed S = 1, 2, & 3 (cases) (ft/sec)
CH-47	8.70 (15)*	15.77 (12)	-19.9 (3)	33.20 (25)*
OH-58	6.86 (144)	13.78 (115)	-8.70 (29)	18.79 (179)
OH-58A-C	5.93 (118)	13.37 (92)	-8.60 (26)	19.23 (149)
OH-58D	11.51 (26)	15.44 (23)	-9.53 (3)	16.67 (30)
UH-60	9.34 (41)	24.36 (36)	-19.66 (5)	35.76 (58)
AH-64	8.36 (35)	22.35 (31)	-29.4 (4)	26.89 (43)

*There are more events with values for the vertical speed than for the vertical velocity in the aircraft frame because all five variables (vertical and ground speeds and the three impact angles) were needed to calculate the set of aircraft frame velocities.

Looking at statistical differences between the aircraft for downward (+) velocity, the OH-58 is different, with statistical significance only for the median. The difference in medians between each pair of aircraft types was evaluated with the Mann-Whitney one-side test for confidence intervals. The significance threshold was set at a value of 0.1. The OH-58A-C was found to differ significantly (Table 3.3) from both the UH-60 and the AH-64. Likewise, the OH-58 D model differed from the UH-60. The differences between the other medians were not significant.

Table 3.3. Comparison* between aircraft types of median aircraft vertical velocity (+ only)

Aircraft	Median (+) Vertical Velocity	Confidence
OH-58A-C	11.25	-
UH-60	21.25	58AC < UH60 by 4.60 to 15.90 ft/sec with 95% conf.
AH-64	20.30	58AC < AH64 by 0.50 to 12.50 ft/sec with 95% conf.
OH-58D	11.20	-
UH-60	21.25	58D < UH60 by up to 18.19 ft/sec with 95% conf
CH-47	8.05	No significance

*Mann-Whitney comparison test

Analyzing the negative vertical velocities did not reveal significant differences between aircraft, undoubtedly due to the small size of the data sets. However, several features of these data are worth commenting upon. First, the number of mishaps with upward impact velocities in the study is 14 pct of the total; that result is driven by the OH-58 with 16 pct. The other three aircraft are experiencing approximately 10 pct of their mishaps with upward impact velocity. Second, the mean velocities for inverted impacts are quite substantial, with the AH-64 having a mean value over 29 ft/sec. Table 3.4 reveals that approximately 49 pct (33/67 in the "total” line) of the impacts with an upward velocity component are actually survivable. However, as might be expected, the fully survivable mishaps include the smallest fraction (< 10 pct 15/203 Column 2 of Table 3.4) of inverted impacts, and the non-survivable group includes the largest fraction (~ 53 pct 34/64 of Column 6 of Table 3.4) of inverted events. Part of this poorer survivability may be due to the high median velocities for inverted crashes.

Table 3.4. Inverted impact velocity survivability

Aircraft	**# V(-) & S=1 (# all S =1)**	**Median V(-) S=1**	**# V(-) & S=2 (# all S =2)**	**Median V(-) S=2**	**# V(-) & S=3 (# all S =3)**	**Median V(-) S=3**
CH-47	2 (13)*	-31.1	2 (4)	-27.1	3 (7)	-32.9
OH-58	10 (132)	-5.9	10 (21)	-14.1	19 (33)	-30.8
UH-60	1 (28)	-11.7	4 (15)	-21.6	9 (17)	-76.5
AH-64	2 (30)	-22.1	2 (6)	-36.7	3 (7)	-16.3
Total	15 (203)		18 (46)		34 (64)	

*The number in parentheses is the number of mishaps in the dataset

The cumulative curves for vertical impact velocity (Figures 2-6 and 2-9) in Section 2.3.2.2 show that the UH-60 impacts at higher velocity throughout the range of impact velocities. The UH-60 curve is the upper curve across the most of the cumulative percent range, but the difference is particularly large in the highest velocity events; i.e., above the 90th percentile. The greater velocity of the UH-60 impacts is noteworthy in light of the fact that its crashworthiness was designed on the basis of impact kinematics from the previous generation of helicopters.

The data presenting the survivable range of crashes are interesting as well. Table 2.8 reports that the two helicopters designed to crashworthiness standards are relatively close to each other in their 95th-percentile survivable velocities; i.e., 51.0 ft/sec for the AH-64 and 53.6 ft/sec for the UH-60. At 48.0 ft/sec, the 95th-percentile survivable vertical velocity for the CH-47 is not much lower than these two newer aircraft. The 95th-percentile survivable impact for the OH-58 is significantly lower than the other three aircraft at 35.0 ft/sec. Looking back to the vertical velocity cumulative percent curve (Figure 2-6), it can be seen that the OH-58 has low impact velocities across the entire percentile range.

A low 95th-percentile survivable impact velocity could be due to poor crashworthiness of the airframe, or it could be due to low operating velocities. To separate out the causation of the low 95th-percentile velocity, data are desired for an aircraft with one parameter high and the other low (see Table 3.5). It is not possible to differentiate based on only the survivable velocity. However, if the velocities for the non-survivable (S=3) events are examined, then a causation may be extracted. It would be expected that the non-survivable accidents will have a higher median velocity than the survivable accidents for the same aircraft type. If the survivable vertical velocities between aircraft types (left side of Table 3.6) are compared, it can be seen that the OH-58 has a lower median impact velocity, but it is not clear why this occurs. If the median velocity of the non-survivable accidents is examined, it may be seen that the OH-58 is also lower than the other aircraft, but it is still not possible to conclude anything about the causation. Finally, if the longitudinal data is examined, once again, it can be seen that the OH-58 exhibits a lower median survivable impact velocity than the other two aircraft. However, the OH-58's longitudinal non-survivable median velocity is comparable to that of the H-60 (in fact, it exceeds it); thus, here it can be concluded that the low survivable velocities at least in the longitudinal direction are attributable to poor crashworthiness, and not to low operation speeds.

Table 3.5. Experiment concept to determine low survivable impact velocity causation

Crashworthiness \ Velocity	Low	High
Low	OH-58	No data
High	No data	H-60 / AH-64

Table 3.6. Comparison of positive median velocities to determine survivability causation

Aircraft Type	Vertical Median Positive Velocity (S= 1& 2)	Vertical Median Positive Velocity (S= 3)	Longitudinal Positive Median Velocity (S= 1& 2)	Longitudinal Positive Median Velocity (S= 3)
H-58	11.3	21.9	13.1	138.7
H-60	21.3	53.0	18.2	108.4
AH-64	20.3	29.1	18.7	47.8

Anecdotally, stories are often heard of pilots who have flown more than one type of helicopter and say that they "feel safer" in an OH-58 than in a helicopter with more designed-in crashworthiness (Reference 9). These pilots generally attribute their preference to the perception that the OH-58 "…is easy to perform a successful autorotation in". Designers also realize that autorotation characteristics are important; consequently, this study has attempted to test or at least evaluate that hypothesis.

Autorotation Index (AI) Correlation with Vertical Velocity

A quantity characteristic of an aircraft's autorotational capability at an instant in time has been suggested (Reference 10) for evaluation purposes. Referred to here as the Autorotation Index (AI), the quantity consists of the product of three design parameters: the total rotor inertia, the rotor disk area, and the rotor rotational speed squared divided by the gross weight (GW) squared. The first three parameters are lumped together for each aircraft and treated as a constant, whereas the GW selected is the estimate from the crash database of the aircraft's weight at the time of the mishap. Table 3.7 lists the values used to calculate the constant "k" and the AI obtained by using the aircraft type's maximum GW. As can be seen by comparing the AI values for different models (e.g., the UH-60A versus the UH-60L) of the same airframe, the GW has a substantial effect on the AI. The hypothesis is that the AI will be predictive of, or at least correlated to, the mean or the 95th-percentile survivable vertical impact velocity. While the values in Table 3.7 go only as high as 77 for the OH-58, a very light OH-58, in the range of 2,150 lb can have an AI value exceeding 275 owing to the GW being squared in the denominator.

Table 3.7. Parameters and values used in calculating the Autorotation Index (AI)

Aircraft	**Omega (rps)**	**Total Inertia (slug-ft^2)**	**Disk Area (ft^2)**	**"k" J*OM^2*S**	**GW (lb)**	**AI (nd)**
UH-60A	27.02	7,060	2,262	1.166E+10	16,450	43.08
UH-60L	27.02	7,060	2,262	1.166E+10	20,250	28.43
AH-64A	30.25	3,800	1,810	6.292E+10	14,770	28.84
AH-64D	31.76	3,800	1,810	6.937E+09	17,500	22.65
OH-58A-C	41.24	724	1,075	1.324E+09	4,150	76.88
OH-58D	41.43	607.2*	962	1.003E+09	4,500	49.51
CH-47C	23.60	15,711*	5,655	4.948E+10	46,000	23.38
CH-47D	23.60	15,711*	5,655	4.948E+10	50,000	19.79

*Estimated

To test for the existence of this proposed correlation, the survivable and partially survivable mishap data from all of the aircraft types were combined together and additional columns were added to the worksheet. One column selected the correct "k" value from a look-up table, and the second added column used the GW at the time of the mishap to calculate the AI at the time of the mishap. This AI specific to the mishap aircraft could then be paired with the vertical velocity of the same mishap. For the purposes of the correlation, only mishaps with positive (downward) vertical velocities were included in the analysis, because the AI would not likely be relevant in an inverted crash. Figure 3-1 shows all of the points plotted with a regression line for all points.

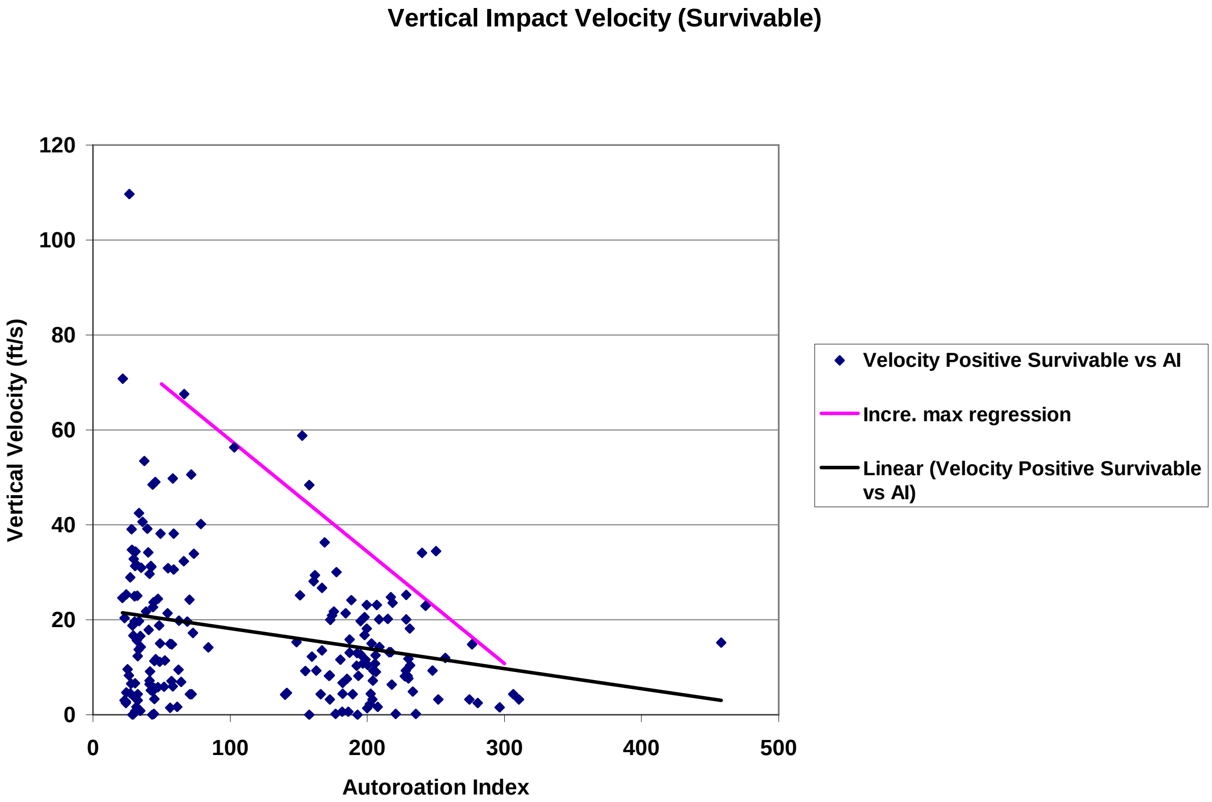

Figure 3-1. Vertical impact velocity for survivable mishaps plotted versus Autorotation Index (eRef 24).

The correlation coefficient between all of the point pairs is only -0.24, indicating a weak correlation. The data pairs were sorted into ascending order according to AI value, and then grouped in increments of 25 AI "units." The mean and standard deviation in each increment were used to calculate the 95th-percentile velocity within the increment. The correlation between the 95th-percentile velocity values for each AI increment and the center value of each increment was tested by calculating the correlation coefficient for a linear regression. The correlation coefficient calculated is -0.79, which suggests a moderately strong correlation (a coefficient of 1.0 is a perfect fit of the data to the line, and 0 indicates pure randomness). However, the velocity values within the increments are not normally distributed; thus, using the Mean and Standard Deviation to estimate a 95th-percentile velocity for each bin has questionable statistical validity. However, encouraged by this strong correlation, the analysts sought to find an equally strong correlation with stronger statistical validity. The correlation between the median velocity value and the center value of the AI increment is only -0.36. The correlation between the maximum velocity in each increment and the AI proved to be quite strong at 0.80, which is slightly stronger than the correlation to the 95th-percentile estimated from the mean. Figure 3-1 shows the regression line for maximum Survivability 1 and 2 vertical velocity values plotted against the AI increment center values. The fact that the AI correlates well with the upper edge of the data suggests that the AI is predictive of some upper limit of the descent velocity. All of the lower velocity values within an increment of AI may simply represent more successfully executed autorotations.

It is worth noting that sorting the data into ascending order by AI also tends to sort the data by aircraft type. Clearly, there is a range of AI values for each aircraft type that is determined by the minimum and maximum gross weights. The lowest two data increments of AI are dominated by AH-64 mishaps, with some CH-47 mishaps mixed in. The upper increments of the AI range are dominated by OH-58 mishaps.

The analysis finds that the correlation between AI and the vertical survivable impact velocity depends on how the vertical impact velocity is chosen. The correlation with all mishaps was not tested. Whether or not AI can be useful as a design tool for crashworthiness depends on the designer's flexibility to manipulate the design factors to increase the AI, thus lowering impact velocity, and still meet the other flight-performance requirements for the design. The development of design tools such as AI is beyond the scope of this study, but there is sufficient promise shown, indicating that more work on AI is merited. A team consisting of a person familiar with these crash statistics, an aerodynamicist or other person with expertise in helicopter flight characteristics, and perhaps a pilot would be most productive.

GROUND_SPEED

Like the VERTICAL_SPEED, the GROUND_SPEED is one of the parameters recorded in the database. The values represent the aircraft's horizontal speed in the earth reference frame. Two parameters are recorded: the magnitude of the ground speed and the direction, forward or reverse. As part of preparing the data for analysis, these two parameters were combined to create an algebraic ground speed with positive being forward. The statistical analysis revealed that the OH-58D has a significantly lower impact ground speed than the UH-60, the CH-47, and the OH-58A-C (See Table 3.8).

Table 3.8. Comparison* between aircraft types' mean ground impact speeds

Aircraft	Mean Speed (ft/sec)	Speed Standard Deviation	Speed Difference (ft/sec)	Confidence (%)
OH-58D	18.95	31.57	-	-
UH-60	51.33	68.36	32.38	97.7
OH-58A-C	37.76	48.33	18.81	92.0
CH-47	56.10	71.30	37.15	92.5
AH-64	35.31	52.00	-	Not Significant

*t-test

<u>Longitudinal Forward Impact Velocity</u>

The cumulative percent curve for longitudinal velocity in the aircraft frame (see Figure 2-6) indicates that the CH-47 has impacts with the greatest longitudinal velocity across most of the percentile range, while the AH-64 has impacts with the lowest longitudinal velocity. The curve further suggests that the OH-58 has the next-slowest impact velocity and, indeed, the statistics support the suggestion that the OH-58D model does have lower longitudinal impact velocities than the UH-60.

The 95th-percentile survivable envelope for the longitudinal and vertical axes (see Figure 2-13) graphically portrays differences between the aircraft. The CH-47 has the highest survivable longitudinal velocity, followed by the UH-60; both exceed 100 ft/sec. The OH-58 and the AH-64 are nearly equal at 83 ft/sec. This result may be explained by the substantial cabin volume behind the cockpit in both the CH-47 and the UH-60. The occupants in the cabin have the benefit of a much greater crush distance than the crew of the same aircraft or the crews in the OH-58 or the AH-64.

Table 3.9 presents the Median and Mean values of the forward impact velocity for the survivable and partially survivable mishaps. Only one statistically significant difference (t-test) was found among the Means, and it is between the OH-58D and the UH-60. The Mann-Whitney comparison test on the medians also finds a significant difference between these two aircraft types. The OH-58D forward impact velocity is less than the UH-60 by 0.01 to 19.10 ft/sec with 91.1-pct confidence.

Table 3.9. Comparison between aircraft types' longitudinal forward impact velocity

Aircraft	Median Velocity (ft/sec)	Mean Velocity (ft/sec)	Velocity Standard Deviation
CH-47	12.50	35.0	42.30
OH-58A-C	13.10	24.63	26.42
OH-58D	11.05	18.73	23.58
UH-60	18.20	33.41	36.49
AH-64	18.70	29.46	35.08

Autorotation Index Correlation with Forward Velocity

The correlation between the AI and forward velocity was tested in the same manner as for the vertical impact velocity. The correlation was found to be even stronger between the 95th-percentile forward velocities in each AI bin and the AI; a correlation coefficient of 0.93 was obtained, compared to 0.79 for the vertical. Once again, however, the velocities values within the bins were not normally distributed. The correlation value between the maximum bin value and the AI is 0.68, which is not as strong a correlation as found for the vertical velocities. Figure 3-2 presents all of the data points used and the regression line through all of the points. The regression line for the maximum velocity for each AI bin against the AI mid-point of the bin is the upper curve in Figure 3-2. Clearly, some aspect of the aircraft's flight characteristic is captured in the AI, which correlates well with the upper edge of the impact velocity of survivable accidents. The forward data for all accidents was not analyzed. Once again, the results suggest that AI may be a useful design parameter, but more investigation is needed into the cause-and-effect relationship.

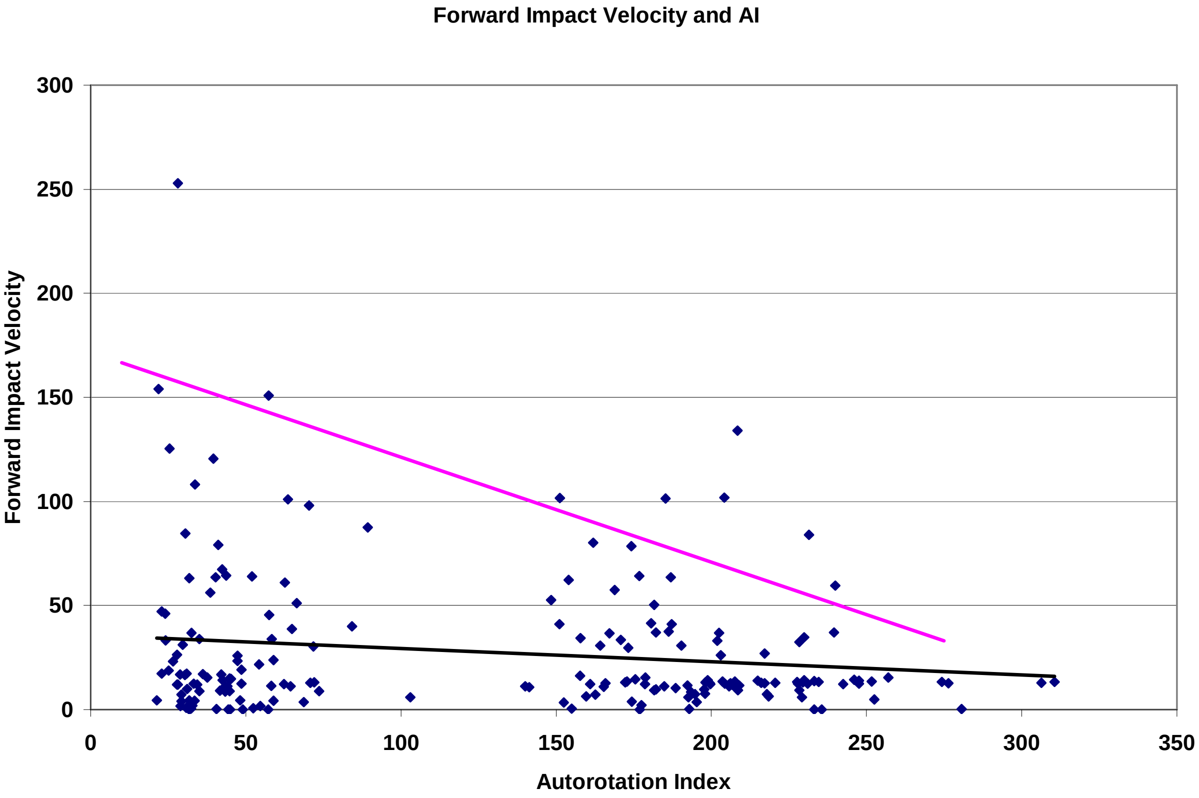

Figure 3-2. Forward survivable impact velocity versus mishap AI (eRef. 25).

Rearward Longitudinal Impact Velocity
Insufficient mishaps occurred with rearward longitudinal velocity to extract any meaningful trends. Table 3.10 reports the number of mishaps with rearward longitudinal velocity by aircraft type.

Table 3.10. Number and mean velocities of rearward impact mishaps

Aircraft	Number of Mishaps (all)	Mean Rearward Velocity
CH-47	1 (22)	-3.8
OH-58A-C	12 (149)	-11.42
OH-58D	5 (29	-4.94
UH-60	9 (57)	-4.73
AH-64	9 (42)	-3.12

Lateral Velocity
Although generally lower in magnitude, the lateral velocity in a mishap is of interest with regard to the lateral impact forces and the lateral structural requirements.

Statistical evaluation of the algebraic lateral velocity lent some credence to the asymmetry observed in the 95th-percentile velocity envelopes (Figures 2-14 and 2-15). Both the OH-58A-C models and the OH-58D model had positive (rightward) mean lateral velocities, whereas the AH-64 had a negative (leftward) mean lateral velocity. The significance of these differences is presented in Table 3.11, along with the mean value for each of the aircraft. None of the other lateral velocities had significant differences.

Table 3.11. Comparison between aircraft types' lateral velocity

Aircraft	Mean Velocity (ft/sec)	Vel. Standard Deviation	Vel. Difference (ft/sec)	Significance level (pct)
AH-64	-5.61	26.76	-	-
OH-58A-C	3.49	24.82	9.1	94.7
OH-58D	2.02	9.69	7.63	90.4
CH-47	-10.40	48.20	-	-
UH-60	1.88	19.56	-	-

Even though the statistics seem to verify that the AH-64 has tendency to crash more frequently to the left, whereas the OH-58 tends to crash to the right, the designer may be more interested in the mean of the absolute lateral velocity. Consequently, the lateral velocities were converted to absolute values and the analysis repeated. Table 3.12 presents the results of this analysis. The CH-47 has the smallest mean lateral impact velocity, followed by the OH-58D.

Table 3.12. Comparison between aircraft types' absolute lateral velocity

Aircraft	Mean Velocity (ft/sec)	Velocity Standard Deviation	Median Velocity (ft/sec)
CH-47	2.74	2.91	2.01
OH-58A-C	6.20	11.92	1.90
OH-58D	3.96	6.91	0.4
UH-60	7.87	11.42	2.60
AH-64	9.82	16.62	4.00

- The OH-58A-C is greater than the OH-58D by up to 1.699 ft/sec (95 pct confidence).
- The OH-58D is less than the UH-60 by 0.01 to 4.10 ft/sec (with 95 pct confidence).
- The OH-58D is less than the AH-64 by up to 5.898 ft/sec (with 95 pct confidence).

While the low values for the absolute lateral velocity may suggest that the designer need not be concerned with the lateral strength of the cabin, the roll and yaw angles should also be reviewed, and the frequency of post-crash rollover evaluated.

Impact Angles

Two angles are related to the forward and vertical velocities: the impact pitch angle, and the resultant velocity angle. The impact pitch angle is the angle recorded in the database for the nose-up or nose-down attitude relative to the horizon of the aircraft at impact. The resultant velocity angle is obtained by taking the inverse tangent of the vertical velocity divided by the longitudinal velocity, and should be approximately equal to the flight path angle.

Pitch Angle (Algebraic)

The pitch angle is treated as an algebraic variable, because the difference between nose-up and nose-down is meaningful to the designer. As indicated in Table 2.11, 50 pct of mishaps occur within 10 deg of level flight (64 pct occur within 15 deg). The histograms of Figures 2-16 and 2-17 do not reveal one aircraft showing a strong trend relative to the others. However, the cumulative percent curve, (See Figure 2-22) suggests that, in absolute terms, the CH-47 impacts at more extreme pitch angles than the other aircraft. The statistical analysis confirms this hypothesis, with the CH-47 having both the highest median and mean pitch angles (See Table 3.13). The statistical tests confirm that the difference is real. The median value for the CH-47 is greater than the OH-58A-C, the UH-60, and the AH-64; these differences are also significant for the means. The median of the OH-58D is also found to be significantly larger than the UH-60 and confirmed by the t-test statistic for the Means. The t-test statistic indicates that the difference between the means of the OH-58D and OH-58A-C models is also significant.

Table 3.13. Median and mean pitch impact angles by aircraft type

Aircraft	Median Pitch Angle (deg)	Mean Pitch Angle (deg)	Pitch Angle Standard Deviation
CH-47	8.00	18.60	38.65
OH-58A-C	3.00	-1.92	29.47
OH-58D	4.50	7.31	24.15
UH-60	-3.00	-1.54	13.74
AH-64	0.00	-2.54	19.59

- The CH-47 is greater than the OH-58A-C by 3.01 to 17.99 deg (with 95 pct confidence).
- The CH-47 is greater than the UH-60 by 2.99 to 21.00 deg (with 95 pct confidence).
- The CH-47 is greater than the AH-64 by 3.02 to 18.00 deg (with 95 pct confidence).
- The OH-58D is greater than the UH-60 by as much as 13 deg (with 95 pct confidence).

Resultant Velocity Angle

Combining the vertical speed and ground speed components forms an estimate of the flight path angle. The Mann-Whitney test on the medians uncovers substantial differences between the aircraft (See Table 3.14). The CH-47 is significantly different from the OH-58D and the UH-60. The OH-58A-C differs significantly from the OH-58D model and from the UH-60 and AH-64. It is interesting that the resultant velocity angle shows the largest difference between the two OH-58 models of all the variables evaluated. Some aspect of the OH-58D model, perhaps the revised rotor system and/or its mission, causes it to crash more nearly vertically.

Table 3.14. Median resultant velocity angle for each aircraft type

Aircraft	Median Resultant Velocity Angle (deg)
CH-47	18.41
OH-58A-C	29.00
OH-58D	65.50
UH-60	71.10
AH-64	49.20

The following relationships are statistically significant for the median resultant velocity angle. The data distributions were not normal enough to use the means for statistical comparisons.

- The CH-47 is less than the OH-58D by 1.98 to 50.25 deg (with 95 pct confidence).
- The CH-47 is less than the UH-60 by 1.88 to 47.63 deg (with 95 pct confidence).
- The OH-58A-C is less than the OH-58D by 15.60 to 45.41 deg (with 95 pct confidence).
- The OH-58A-C is less than the UH-60 by 12.69 to 35.80 deg (with 95 pct confidence).
- The OH-58A-C is less than the AH-64 by 0.20 to 27.00 deg (with 95 pct confidence).

Roll Impact Angle

Similar to the pitch angle, many mishaps are clustered around level attitude, with 52 pct of the mishaps occurring at a roll angle within 10 deg of 0 (See Table 2.12). The frequencies in this table suggest an overall bias to positive (rightward) roll. The cumulative percent plot (See Figure 2-23) suggests that the CH-47 and the AH-64 tend to impact at higher absolute roll angles than do the other aircraft.

Looking first at statistics on the algebraic (+ & -) roll angles, the median values suggest that there is not a strong bias. However, both the UH-60 and AH-64 have high mean values (See Table 3.15). Looking back to Figure 2-18, there is a cluster of mishaps for these two aircraft between 90 and 180 deg of right roll. These have little effect on the median, but raise the mean because the values are large and they are not offset by a smaller cluster of events at left roll 90 to 180 deg. The only statistically significant difference between the algebraic roll values is that the OH-58A-C is less than the AH-64 by up to 22 deg with 95 pct confidence.

Table 3.15. Median and mean algebraic roll impact angles by aircraft type

Aircraft	Median Roll Angle (deg)	Mean Roll Angle (deg)	Roll Angle Standard Deviation
CH-47	-3.0	2.54	25.52
OH-58A-C	0	-3.22	33.1
OH-58D	2.0	2.0	46.8
UH-60	2.0	13.19	46.67
AH-64	3.0	20.71	49.59

On the basis that roll might be expected to be an inherently symmetrical variable, the absolute values were also explored. Once again, the UH-60 and the AH-64 tend to exhibit the higher angle mishaps (Table 3.16), but the differences are not further accentuated. The median absolute roll angle of the AH-64 is larger than the median of the OH-58A-C by up to 15 deg.

Table 3.16. Median and mean absolute roll impact angles by aircraft type

MTDS	Median Roll Angle (deg)	Mean Roll Angle (deg)	Roll Angle Standard Deviation
CH-47	3.00	12.08	22.37
OH-58A-C	8.00	19.32	27.01
OH-58D	8.00	27.62	37.38
UH-60	10.00	23.03	42.57
AH-64	20.0	32.45	42.59

Yaw Impact Angle

The yaw angle is even more concentrated around the neutral position. Almost 62 pct of mishaps occur within 10 deg of forward (Table 2.13). Looking at the cumulative percent curve indicates that the AH-64 experiences the greatest yaw excursions at impact. The statistical analysis has been applied only to absolute values of the yaw data. As might be expected, the CH-47 has a smaller mean yaw angle than the OH-58A-C, the UH-60, and AH-64 (See Table 3.17). The twin-rotor design of the CH-47 is less susceptible to loss of yaw authority, and thus less likely to impact at a yaw angle different from 0. However, the differences were not statistically significant.

Table 3.17. Median and mean absolute yaw impact angles by aircraft type

Aircraft	Median Yaw Angle (deg)	Mean Yaw Angle (deg)	Yaw Angle Standard Deviation
CH-47	3.00	7.15	10.06
OH-58A-C	3.00	19.17	37.22
OH-58D	10.0	17.73	23.16
UH-60	9.5	23.03	36.81
AH-64	10.0	35.6	52.6

Post-crash rollover

One concern for designers of the aircraft structure is post-crash rollover. An examination of that variable for all mishaps reveals that post-crash roll angles are reported in more than half of the AH-64 incidents and nearly one third of the UH-60 events (See Table 3.18). Both the OH-58D and the AH-64 have post-crash roll angles reported for half of their mishaps, whereas the number reported for other aircraft are significantly lower.

Several parameters (12) are possible influences on the tendency of a helicopter to roll over during or after a crash: rotor inertia, cabin configuration (side-by-side or tandem), type of landing gear (skid or rolling), type of landing gear (rigid, damped, or energy-absorbing), landing gear track, height of aircraft c.g. on landing gear or static stability factor[8] (landing gear track / [2 * height of c.g.]).

The difference in rollover propensity between the OH-58A-C and the OH-58D is remarkable. The major difference between the models is their rotor configuration; the older OH-58A-C models have a high-inertia two-blade rotor and very low percentage of mishaps with post-crash rollover, whereas the OH-58D model has a lower-inertia, four-blade rotor and a higher probability of rolling over. Information provided by Bell to the author indicates that the static stability factor for the OH-58C is 0.66[9], the OH-58D with "rapid deploy" skid gear is also 0.66, and the OH-58D with the standard skid gear is 0.67. The fact that these values are virtually identical for two aircraft with such different behavior indicates that the static stability factor likely is not a good predictor.

Comparing the UH-60 to the AH-64 (Table 3.18), with both aircraft designed at similar times and to similar standards, suggests that the narrow tandem configuration may be more likely to roll over than the broader side-by-side configuration.

In regard to skid gear versus rolling gear, the vast difference in rollover rate between the OH-58A-C and the OH-58D, which have identical skid gear, suggest that skid or rolling is not the predominant factor. Although the CH-47 has rolling landing gear, it is not readily comparable to any of the other aircraft because it has quad landing gear rather than tricycle landing gear.

Table 3.18. Number of mishaps with reported post-crash roll angles*

Aircraft	**Number with Post-Crash Roll**	**Total Mishaps in Study**	**Percent of Mishaps with Post-Crash Roll**
CH-47	2	25	8
OH-58A-C	13	157	8
OH-58D	15	32	47
UH-60	18	60	30
AH-64	25	44	57
All	73	318	23

The design of the landing in regard to its energy-absorbing capacity has also been suggested as affecting rollover propensity. Table 3.19 groups the aircraft by landing gear type. The skid is rigid until the landing force exceeds a critical value; above that force level, the skid collapses and absorbs energy in the process. The CH-47 landing gear is of the “oleo” design which provides some damping, but minimal energy–absorption, capability. The UH-60 and the AH-64 landing

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[8] The Static Stability Factor suggested here is the one proposed by NHTSA (Reference 13). Higher values imply greater stability. Clearly there are several ways this could be defined, but this definition captures the effect.

[9] For comparison purposes, a typical passenger car has track = 60 in. and c.g. = 20 in. giving an SSF= 1.5 and a typical SUV has a track= 58 in. and a c.g.= 29 in. giving an SSF= 1.0, i.e. significantly less stable than a passenger car.

gear are designed to absorb substantial amounts of impact energy and both conform to MIL-STD-1290 requirements in this regard. Table 3.19 groups the aircraft according to their gear design. Even though combining the types obscures large differences between the OH-58A-C and OH-58D and also between the UH-60 and the AH-64, it still strongly suggests that aircraft with the energy-absorbing rolling landing gear are more vulnerable to rollover than those with skid type landing gear.

Lastly, it has been suggested (12) that at least the AH-64's propensity to post-crash rollover could be exacerbated by its high landing gear stance in order to provide clearance for the under-slung nose gun. This suggestion might be analyzed by calculating the Static Stability Factor for each aircraft and comparing the result. Sikorsky provided the information necessary to calculate the static stability factor for the UH-60: at a gross weight of 16,855 lb, the static stability factor is 0.75 (indicating greater stability than the OH-58) and at 22,000 lb, the SSF is increased to 0.81 due to a lower c.g. caused by deflection of the landing gear. Unfortunately, no data were available for the AH-64 as this report is being finalized.

*All mishaps regardless of survivability.

Table 3.19: Number of Mishaps with reported post-crash roll angles. Organized according to support design[1]

Aircraft	Number with Post-Crash Roll	Total Mishaps in Study	Percent of Mishaps with Post-Crash Roll
CH-47	2	25	8
OH-58	28	189	15
UH/60 & AH-64	43	104	41
All	73	318	23

Empirical Regression Model

The least-squares method was used to explore possible linear models built up from the quantitative variables in this study. The software selected data from the list of quantitative variables and tested them to see if the independent variable could predict the dependent variable with reasonable residual values. This method assumes that the errors are normally and independently distributed about a mean equal to 0 and having a constant variance. The errors from this ideal are the residuals, which are the difference between the actual dependent value and the dependent value predicted by the model. The software tests each variable in turn, deciding (based on the residuals) whether or not to include it into the model. The software found no linear models with satisfactory residuals. The independent variables tested were: aircraft weight; MSL altitude; AGL altitude; airspeed; resultant velocity angle; vertical impact force; longitudinal impact force; lateral impact force; and pitch, yaw, and roll angles at impact.

No significant models with acceptable residuals were found. Two relationships showed some statistical promise: one between the algebraic vertical speed and the airspeed, and the other between the airspeed and the AGL altitude. However, the residuals violated the constant-variance assumption; as the predicted value increased, the variance grew even faster. Models were attempted to predict dependent variables including: vertical impact force, longitudinal impact force, lateral impact force, forward velocity, vertical speed, and ground speed. Various transformations of the data were attempted correct the problems, but no transformation was able to correct the discrepancies. To give the reader some idea of how weakly predictive these test models were, a measure called R^2_{adj} can be calculated. This value expresses the fraction of the total variability in that data that is explained by the model's prediction. A perfect model predicts 100 pct of the variability (value changes) in the dependent variable from the variability in the independent variables. The best models tested in this effort did not exceed 10 pct.

This study did not test for relationships more complex than linear. Looking for relationships more complex than linear will be better approached from a knowledge of the flight dynamics rather than from a purely statistical perspective. It may be possible to achieve a "fit" to almost any data with a sufficiently high-order polynomial, but the relationship likely will have no useful mechanistic basis. Likewise, in this study, other forms of relationships could be randomly explored for statistical significance, but this study team has no basis to sort the meaningful from the non-meaningful. Even though there appear to be a great many data points in this study, the number has often proven inadequate to draw conclusions.

Impact Design Scenarios

At least as early as 1971, the CSDG (Reference 1) made recommendations for design scenarios. By creating design scenarios, the inherently chaotic, random nature of crashes may be transformed into manageable and quantifiable objectives with which the aircraft design team may work. Table 4.1 summarizes the design scenarios as they appear in MIL-STD-1290A. In three cases, the main scenario is broken down into two variations. In this section, the scenarios will be addressed in the order presented in Table 4.1. Ideally, design scenarios should not only reflect “real-world” impacts and conditions, but should also reflect the fact that an aircraft is first and foremost built to perform a mission.

The approach of this section is to review the data and analysis described in the previous sections and evaluate the existing design scenarios against these findings.

Longitudinal Impact

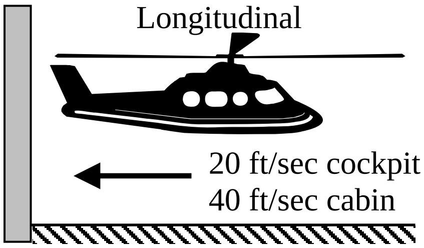
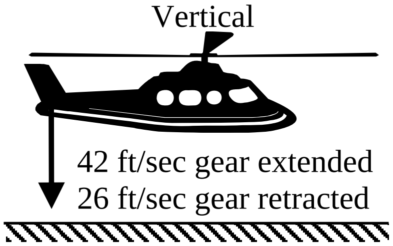
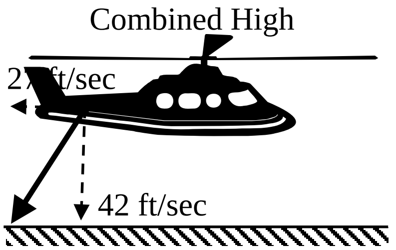
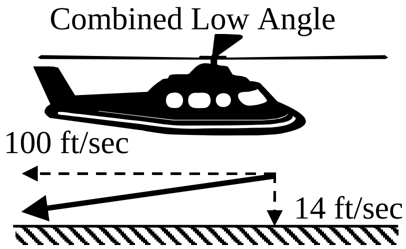
The longitudinal impact scenario states that the aircraft must be capable of maintaining an occupiable volume, restraining the occupants and cargo, and preserving egress in a pure forward crash into a vertical barrier. It must provide this level of protection up to 20 ft/sec for cockpit occupants and 40 ft/sec for cabin occupants. Although few crashes occur in this extreme condition, nor the equivalent (a vertical crash nose-first into flat terrain), by specifying a perpendicular impact into a rigid barrier, the scenario creators have set the velocities for the worst-case impact orientation. Thus, in the real-world mix of impact orientations, the occupants will be protected in the longitudinal direction for any crash whose longitudinal component remains within the design guideline. The following discussion will look first at the longitudinal velocity, then at events where the aircraft axis is aligned with the velocity vector, and finally at events where the impact surface is perpendicular to the aircraft’s longitudinal axis.

Longitudinal Velocity

Despite the differences in methodology, a comparison of the three major studies suggests that the forward impact velocity of survivable helicopter crashes is increasing. Figure 4.1 (similar to Figure 2-13) compares the longitudinal velocities in the three different studies. This plot reveals that the original CSDG curve crossed through the 20-ft/sec guideline at only about 15 cumulative pct. The Shanahan curve indicates that the velocity level enunciated in this scenario would be beneficial in upwards of 72 pct of the events. The curve resulting from this study indicates that the protection level in the scenario protects in approximately 65 pct of all mishaps with forward velocity. As discussed above, in fact, the guideline is protective to significantly higher velocities, because the aircraft is not aligned along the flight path.

The 40 ft/sec velocity specified for the cabin crosses both the CSDG curve and the Shanahan curve at approximately 85 pct. The current study indicates that the 40 ft/sec will exceed 75 pct of all mishap forward velocities.

Table 4.1. Summary of crash impact design conditions of MIL-STD-1290A

Number	Condition	Surface	Intent
1 2		Rigid Vertical Barrier	Skidding aircraft encounters rigid object. Maintain occupiable volume, preserve egress routes, and retain occupant and cargo restraint attachments.
3		Rigid Horizontal Surface	Vertical impact within -5 to +15 deg pitch and ±10 deg roll. Maintain occupiable volume and prevent injurious accelerative loading.
4 5	30 ft/sec rotary wing		Impact at 90-deg roll angle. Maintain occupiable volume and minimize chance of trapping occupants and their extremities between aircraft and impacting surface.
6			High angle impact with gear -5 to +15 deg pitch and ±10 deg roll. Maintain occupiable volume.
7		Plowed Soil	Low angle impact with gear extended, 5-deg nose-down pitch, and within ±10 deg roll and ±20 deg yaw. Maintain occupiable volume, preserve egress routes, retain occupant and cargo restraint attachments, and prevent earth plowing and scooping.
8	Rollover, Side Impact. (Static requirement)	Soil	Aircraft penetrates soil 2 in. Maintain occupiable volume
9	Rollover, Roof Impact		Maintain occupiable volume

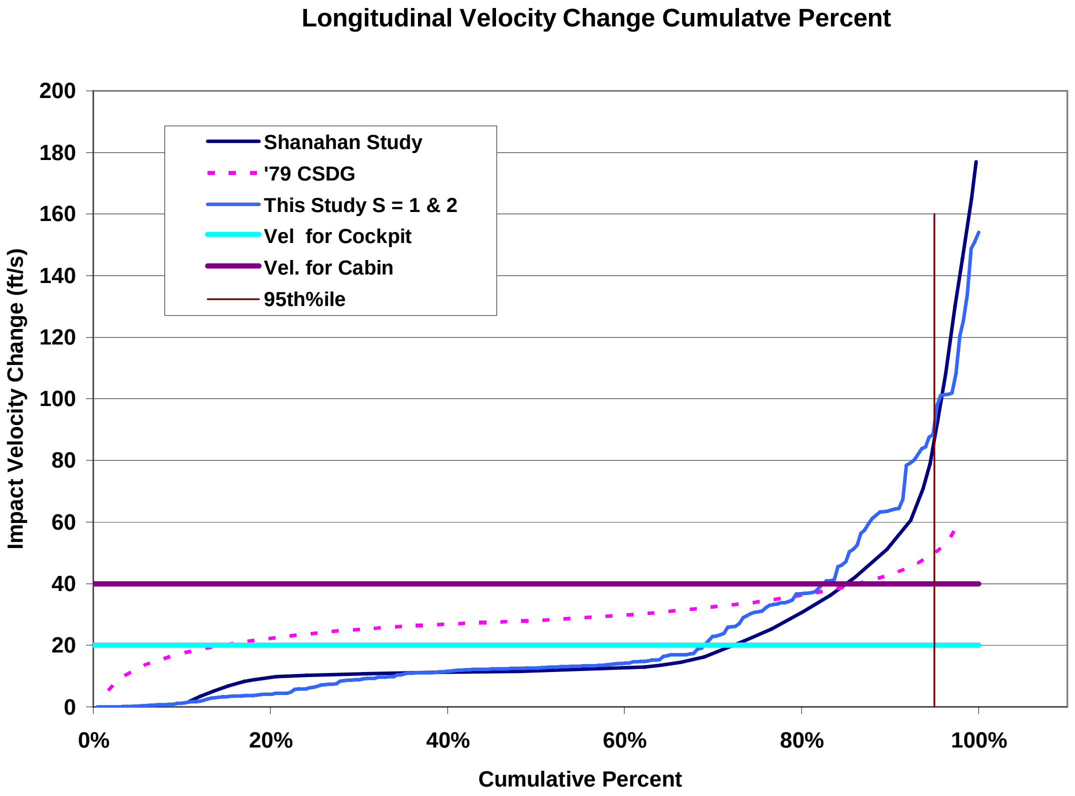


Figure 4.1. Longitudinal velocities from the three studies with longitudinal design scenario (eRef. 26).

Looking at the 95th-percentile survivable events in relation to the longitudinal design criteria, many events are survivable at velocities that exceed the design guideline (Table 4.2). The study to develop the ’79 CSDG data would not have included any aircraft that were designed to crashworthiness standards; whereas the Shanahan study and this study include increasing fractions of crashworthy aircraft (Shanahan 8.8 pct, this study 33 pct). This increasing number of crashworthy aircraft may explain in part the increase in survivable forward velocity for mishaps. While it would be tempting to look at these increasing velocities as a call for increasing the crashworthiness design velocities, these higher numbers in fact imply that aircrews and passengers are surviving increasingly more severe mishaps.

Table 4.2. Longitudinal design and threshold velocities

Data Source	Longitudinal Velocity (ft/sec)
This study - 95th-percentile survivable all A/C	93.0
Shanahan - 95th-percentile survivable	83.6
’79 CSDG - 95th-percentile survivable	50.2

Cabin Design Guideline MIL-STD-1290	40.0
Cockpit Design Guideline MIL-STD-1290	20.0

<u>Longitudinal Impacts</u>

The wisdom of setting a longitudinal design condition is confirmed by looking at the number of crashes that occur with the longitudinal axis of the aircraft aligned within a cone formed by pitch and yaw angles less than 26 deg (26 deg is chosen because cosine 26 is 0.90, so the longitudinal velocity component is reduced only 10 pct) away from the flight path (i.e., the normal flight mode for a fixed-wing aircraft). It should be noted that this set of criteria represents a relaxation of the criterion (the impact surface need not be perpendicular to the flight path and longitudinal axis of the aircraft) from those in the first paragraph of this section. If all the mishaps with these criteria are queried, the results show that about 27 pct of the mishaps in this study occurred where the aircraft impacted within 26 deg of nose-first. Thus, slightly more than one in four crashes occur in a nose-first attitude; thus, the design condition that effectively establishes longitudinal crashworthiness is highly relevant.

<u>Longitudinal Impact into Perpendicular Ground Surface</u>

In this scenario, the first step is to further refine the query to estimate the fraction of events that will fall within a similar margin of the first design condition where the ground is the impact surface. First, the aircraft attitude must be aligned along the velocity vector. This criterion will be set by requiring that the resultant velocity angle plus the pitch angle equal 0 (the nose must be pitched down equal to the angle of the velocity above the horizontal). Next, allow a margin of 26 deg on either side of 0; 26 deg being selected on the basis that the cosine of 26 deg is 0.90, and thus the velocity component along the true direction will be greater than 90 pct of the maximum value. It is also a requirement that the yaw angle be less than 26 deg off of the flight path. Thus, the longitudinal axis of the aircraft is aligned within a cone of 26 deg off of the flight path. Now, to ensure that the impact occurs on the nose, it is required that the resultant velocity angle plus the slope angle equal 90 deg. Again, a 26-deg margin is allowed so as to include all the events with velocity components greater than 90 pct in the impact direction. There are several caveats: 1) by using the slope from the database, the highest value is being assumed, because the flight direction relative to the slope direction is not known (the worst error would be that the slope should be subtracted from, rather than added to), 2) four angles are involved; by allowing a range on each angle, the possibility exists that the angles will be additive and the result will fall outside the range. Thus, it might be expected that the number of mishaps included in the query will be somewhat higher than really fits that which is being searched. Surprisingly, the query finds only one event that satisfies all of the criteria out of 287 for which all the necessary information is available. The one event was an impact into a very steep slope.

As stated in the earlier paragraph, and as will be seen in the discussion of Conditions 6 and 7, a large fraction of events do occur with the nose impacting first. By setting a strong design requirement in this condition, protection is provided for a wide range of related, if not identical, events.

The query above finds only one perpendicular impact into the ground, but it does not consider impacts into obstacles . Looking at Table 2.16, Impact Surface Descriptors, which includes obstacles, trees are far and away the most likely obstacle on the impact site. (It should be noted that creating a similar query to the one above for impacts into vertical obstacles represents another level of complexity that is beyond the scope of this study.) Even combining buildings with the "other" category, the total of those occurrences is less than one-fourth of the occurrences of trees. Thus, in reviewing this design scenario, rather than adjusting the velocities, the authors would explore a move in the direction of changing the guideline to a pole-intrusion-type scenario. Instead of specifying that the occupiable volume and egress routes be preserved in the cockpit at the specified velocity upon impact with a flat vertical surface, it would be specified that a circular wooden obstacle of an established diameter not be permitted to intrude into the occupiable volume far enough to injure the aircrew. As in the existing scenario, a higher velocity should be set for the cabin. While this scenario potentially will be more difficult to meet than the existing scenario, it reflects an aspect of the crash environment experienced by the Army aircraft. However, before moving forward with such a change in the design condition, additional work on analyzing the data to extract the frequency of these events is recommended.

Vertical Impact

Condition 3 represents the idealized survivable helicopter crash, a pure vertical descent where maximum energy absorption can be extracted from crashworthy features such as the landing gear, crushable subfloor, and stroking seats. The section will look first at the findings for vertical velocity and then specifically at the design scenario.

Figure 4.2 presents the cumulative vertical mishap velocities from the three studies with the vertical design scenario velocities superimposed. Looking at the scenario with landing gear first, it may be noted that, based on the CSDG information, 42 ft/sec fell right at the 95th-percentile level. In fact, the CSDG results probably provided the basis for this requirement. The Shanahan study is slightly higher, with approximately 97 pct of survivable events falling within the guideline velocity, whereas this study has approximately 10 percentage points fewer mishaps within the guideline at 85 pct.

Looking at the data relative to the guidelines (see Table 4.3), a somewhat different situation can be seen than for the horizontal. The results of the Shanahan study indicate reduced survivability compared to the numbers developed by the CSDG study, whereas this study shows a significant increase compared to the Shanahan study. In as much as this study includes more mishaps involving aircraft designed to the crashworthiness standards than the Shanahan study did, it is reasonable to conclude that the standards have contributed to the increased survivability indicated by the higher 95th-percentile velocity obtained in this study.

A similar query is conducted to identify how many events are similar to the vertical condition. The criteria are as follows: A) the resultant velocity angle plus the slope must fall between 64 and 116 deg, B) the slope angle minus the pitch angle must fall between +25 and -15 deg (using the narrower allowable range for pitch in this scenario), and C) the roll angle must fall between +/- 10 deg. This query finds 8.7 pct (25/287) of the mishaps fall within this criterion. Of these 25 downward impacts onto the belly in the aircraft reference frame, 17 were all or partially survivable.

Lateral Impact

The lateral guideline calls for a design impact velocity of 30 ft/sec for rotary-wing aircraft. Although the CSDG and the Shanahan paper did not look at the lateral impact velocities in as much detail as the vertical or longitudinal, this study developed data on the lateral velocities.

The results for the means of the absolute value lateral velocities (Table 3.12) are quite low, with none of the aircraft types exceeding 10 ft/sec. Information in Table 2.10 on the 95th-percentile velocities in the rightward direction reveal values that are somewhat higher than the 30 ft/sec requirement.

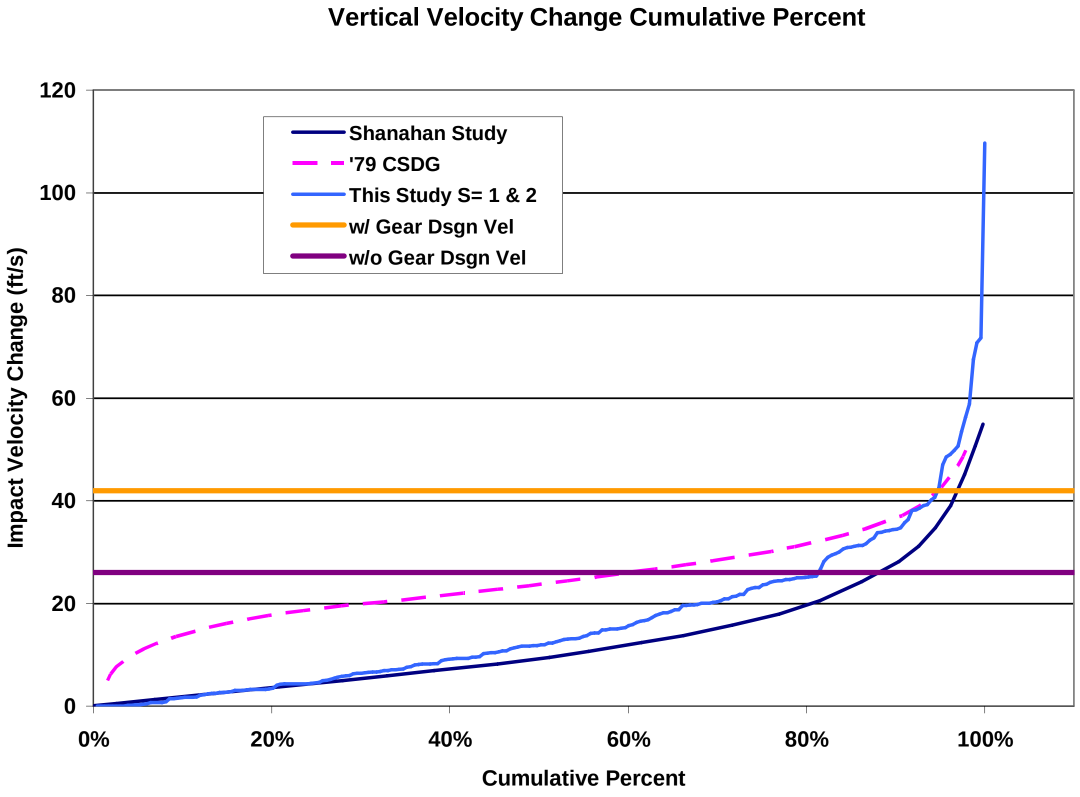


Figure 4-2. Vertical velocities from the three studies with vertical design scenario (eRef. 31).

Table 4.3. Vertical design and threshold velocities

Data Source	Vertical Velocity (ft/sec)
This study 95th-percentile survivable all A/C	48.4
Shanahan 95th-percentile survivable	36.7
’79 CSDG 95th-percentile survivable	42.0
Design Guideline with Gear MIL-STD-1290	42.0
Design Guideline without Gear MIL-STD-1290	26.0

Creating a query to identify the number of mishaps falling within this design condition involved testing for the pitch axis aligned along the velocity direction (Yaw = + or – 90 deg), testing for the velocity direction to be perpendicular to the ground, and testing for the side of the aircraft to be parallel with the impact surface, again allowing a range of plus or minus 26 deg. The pitch angle was not limited.

This query found 2 pct (6/302) of the mishaps that were similar to the design condition. Of these six mishaps, four were survivable or partially survivable. It is interesting to observe that all of the survivable mishaps were impacts on the right side.

Combined-High-Angle and Combined-Low-Angle impact

The two combined-velocity impact scenarios have resultant angles of 57 deg for the high-angle impact and 8 deg for the low-angle impact. Table 4.4 compares some of the relevant values for these two scenarios. The resultant velocity angle is obtained by the inverse tangent of the vertical impact velocity divided by the horizontal impact velocity. The low-angle impact scenario appears to be set too low based upon these data, relative to the actual events, even for the H-47 and older models of the OH-58A-C. At 57 deg, the high-angle impact event is nicely centered between the angles of the AH-64 below it and the OH-58D and H-60 above it.

Table 4.4. Comparison of design resultant velocity angles to combined design scenarios

Identifier	Angle (deg)
H-47 Median Resultant Velocity Angle	18.4
OH-58A-C Median Resultant Velocity Angle	29.0
OH-58D Median Resultant Velocity Angle	65.5
H-60 Median Resultant Velocity Angle	71.1
AH-64 Median Resultant Velocity Angle	49.2
High Angle Design Scenario MIL-STD-1290	57.0
Low Angle Design Scenario MIL-STD-1290	8.0

The same information is presented graphically in Figure 4-3 overlaid on the data points for all the mishaps on the study. This presentation emphasizes the fact that these scenarios are not really angles, but are single points in velocity space. Consequently, their position relative to all the accident velocities and relative to the 95th-percentile survivable events should be examined.

The high-angle impact scenario is already exceeded by the 95th-percentile survivability curve. With aircraft designed to crashworthiness standards (H-60 and AH-64) constituting only 35 pct of all mishap aircraft in this study, it should be expected that the 95th-percentile survivability curve will move further outward toward higher velocities. Referring back to Table 2.8 for the survivable velocities by aircraft, it was noted that the H-60 and the AH-64 are achieving substantially higher 95th-percentile survivable vertical velocities compared to the OH-58. Since the high-angle impact scenario is dominated by the vertical velocity, it can be expected that the curve will continue to move beyond the point representing the design scenario.

The low-angle impact scenario lies just below the “100” on the X axis beyond the 95th-percentile survivable curve, but well inside the curve for the 95th-percentile of all events. Although the scenario point lies outside the 95th-percentile survivable curve, it might be argued that the 95th-percentile curve can be expected to move outward in the future. Referring back to Table 2.8 for the survivable velocities by aircraft, it can be seen that indeed the H-60 has an increased 95th-percentile forward velocity of 107 ft/sec compared to the OH-58's 83.5 ft/sec. However, the AH-64 has only equaled the OH-58's 95th-percentile forward velocity; thus, it will contribute nothing to increasing the survivable forward velocity component of the curve.

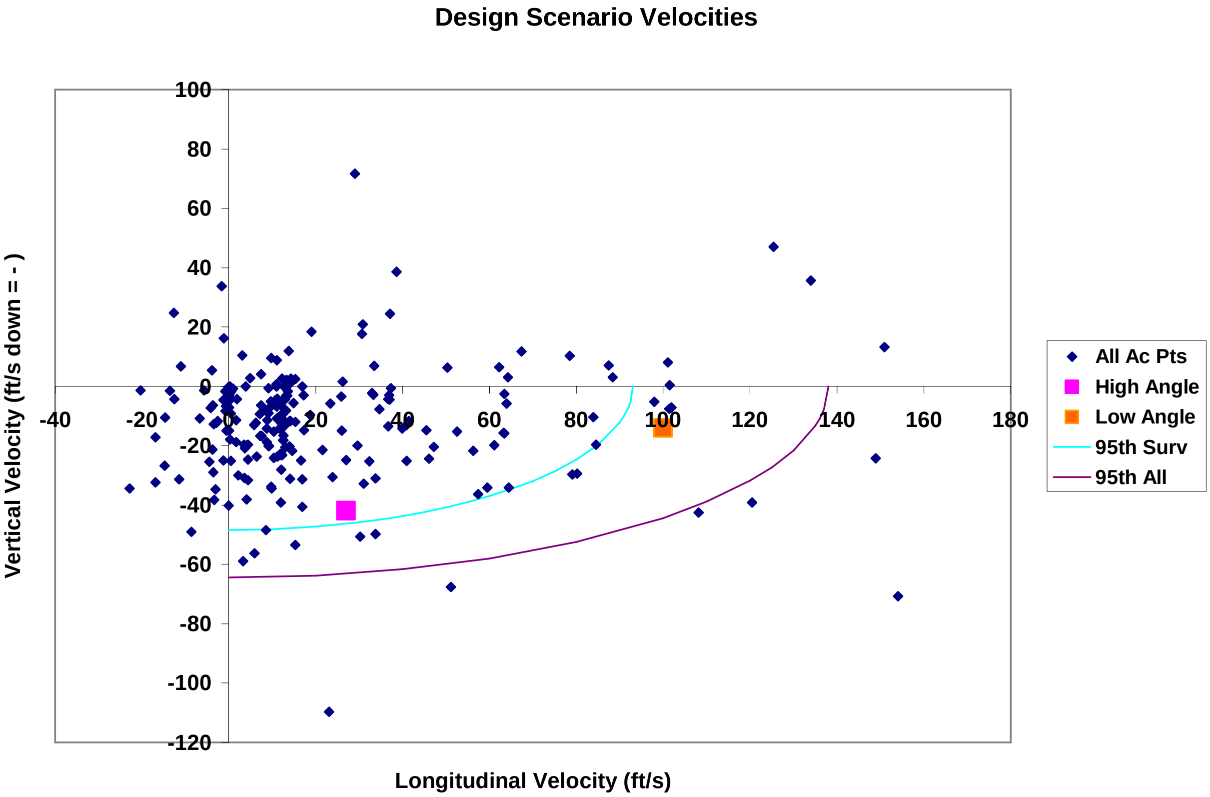


Figure 4-3. Comparison of high- and low-angle scenarios to study data (eRef 5).

Queries like those used in earlier sections were constructed to identify mishaps that are similar to the combined-high-angle and combined-low-angle design conditions. Both of these queries identified a significant number of mishaps, as might be expected by looking at Figure 4-3. These queries can be visualized first as "rays" extending from the origin through the two design points on Figure 4-3, and these rays opening up to 26 deg on either side of the ray. Since attitude is taken into account, not all of the points shown in the plot will be included in the query. It should also be noted that there is a small overlap in the query between 31 and 34 deg, where mishaps will be counted in both conditions.

The query on Condition 6, the combined-high-angle impact event, found 9.8 pct (29/287) of the mishaps occur near this condition and 8.0 pct (23/287) are survivable. The query on Condition 7, the combined-low-angle impact event, is similarly fruitful, finding 10 pct (29/287) of the events are near the stated conditions and 7.3 pct (21/287) are survivable. Regardless of the fact that none of the median resultant velocities for specific aircraft fall near this design condition, this condition is representative of a substantial number of events.

In summary, the low-angle impact scenario represents a goal that has yet to be achieved on a fleet basis. However, at least one aircraft, the UH-60, appears to be capable of meeting it. The high-angle impact scenario represents a goal that the fleet is exceeding and can expect to exceed by even wider margins in the future.

Rollover Impact

Rollover Impact, Side

The rollover, side-impact design scenario is more of a post-crash condition than an impact condition, since no velocity is specified. However, there are data for post-crash rollover, so a query was constructed for this design condition. The query was constructed to simply capture all events in which the aircraft had a post-crash roll of greater than 64 deg (90 deg for a roll onto one side minus 26 deg to open up the tolerance consistent with other queries) either way. Without imposing the condition that the event occur on soil, the query returns 14 pct (43/318) of all events and 9.1 pct (21/318) survivable events. It should be noted that many of the data cells for post-crash roll were left blank, so a 0 was inserted into these cells to facilitate the analysis. To more closely simulate the specified design condition, a second query was created that also required that the mishap occur on soil ("sod" is the actual surface specified in the database). Although tightening of the criteria reduced the number of mishaps returned, this design condition still remains representative of a significant number of events. The soil-constrained query returned 10 pct (32/318) of all the events, and 6.6 pct (21/318) were survivable.

Inverted Crashes

While there is no design condition for inverted crashes, they do occur with significant frequency. By defining a crash with negative vertical velocity component as an inverted crash, a number of events can be extracted from the study data. What is not surprising about the data in Table 4.5 is the right side of the table, where the data indicate that roughly half of the inverted mishaps are non-survivable. If anything is surprising in this table, it is that half of the inverted crashes are rated as at least partially survivable. What is also surprising is that at least 11 pct, and in the case of the OH-58 nearly 19 pct, of the inverted events prove to be survivable, even with fairly high vertical velocity components.

Table 4.5. Inverted crashes by aircraft type

Aircraft	Number of Survivable Inverted Mishaps	Inverted Mishaps as Percent of Survivable Mishaps	Range of Velocities (ft/sec)	Number of Non-survivable Inverted Mishaps	Inverted Mishaps as Percent of Non-survivable Mishaps	Range of Velocities (ft/sec)
CH-47	4	25	5 to 57	3	33	5 to 55
OH-58	29	19	1 to36	16	48	4 to 97
UH-60	5	12	12 to 39	9	53	5 to 183
AH-64	4	11	2 to 72	4	57	5 to 267

These data suggest that the inverted crashes should not be dismissed out-of-hand as non-survivable, nor as not susceptible to crashworthiness design considerations.

Summary

It is hoped that the survival percentages in the last column of Table 4.6 might be somewhat higher than the overall survivable rate for the study of 79 pct. If these rates were higher than the study rate, one might conclude that the design conditions were having a positive effect on the outcome of crashes. However, it should be recalled that approximately 67 pct of the mishaps in the study involve aircraft that were not designed to these conditions. Thus, it is somewhat premature to draw such an over-arching conclusion. Queries on a specific aircraft type may help to clarify the issue, but the number of events will be small for either the AH-64 or the UH-60, and so small changes in the number of survivable events will cause large percentage changes.

Table 4.6. Summary of the design conditions and frequency of matching mishaps

Design Condition	% of All Mishaps Similar to Condition	% of All Mishaps Like Conditions & Survivable	% of Mishaps Like Condition which are Survivable
1. & 2. Longitudinal	0	0	0
3. Vertical	8.7	5.9	68
5. Side Impact	2.0	1.3	67
6. Comb. High Angle	9.8	8.0	82
7. Comb. Low Angle	10	7.3	72
8. Post-crash Roll on Soil	10	6.6	66

Conclusions and Recommendations

The design decisions necessary to meet an aircraft's performance requirements and yet provide a reasonable level of crashworthiness are up to the design team. The author's intent in this study is to use the statistics of completed mishap investigations to provide a quantitative basis for making those decisions. While gathering and analyzing data such as these will never reduce the decisions (and sometimes trade-offs) to mere calculations, simply providing feedback on how different designs have performed in crash scenarios will be beneficial. The selection of events in this study provides the additional benefit of including a significant number of events involving aircraft designed to the current generation of crashworthiness standards.

Whereas past studies have concentrated mainly on providing the designer with information about survivable accidents, this study endeavors to provide information on all mishaps. This additional information is intended to provide decision-makers with quantitative information on the incremental benefits to be gained, and provide designers with the information on the incremental performance required to achieve those benefits.

conclusions

This study to update the kinematic design criteria for helicopter crashworthiness has found that the crash environment for helicopters, as represented by these four types, has continued to evolve in the direction of higher velocities at impact and more diverse attitude angles at impact (See Table 5.1). The rather dramatic increase in forward velocity was presaged in Shanahan's 1989 study. However, in view of the substantial advances in technology represented by comparing the performance capabilities of the AH-64 and the UH-60 to the performance capabilities of the OH-58A-C and the CH-47, the presence of only one dramatic change is somewhat surprising.

Table 5.1. Comparison of key kinematic parameters between studies

	CSDG '79	Shanahan '89	This study '04
95th-%ile Vertical Velocity Survivable	42.0 ft/sec	36.7 ft/sec	48.4 ft/sec
95th-%ileHorizontal Velocity Survivable	50.2 ft/sec	83.6 ft/sec	93.0 ft/sec
Pitch Angle* (pct within 15 deg of 0)	90 pct	67 pct	64 pct
Roll Angle* (pct within 15 deg of 0)	79 pct	79 pct	60 pct
Yaw Angle* (pct within 15 deg of 0)	80 pct	78 pct	71 pct

* Angle statistics in the Shanahan study and this study include all mishaps. The CSDG included only survivable accidents.

<u>Impact Velocity</u>

In the early studies, the events included were only those that were survivable and partially survivable. The value highlighted and discussed at length was the 95th-percentile velocity, which the text suggested as a desirable design goal. Later revisions of the Design Guide chose not to include the cumulative percentile charts, and stopped referring to the 95th-percentile survivable crash velocities. The reasoning behind this action was that, as data from aircraft designed with greater consideration for crashworthiness were included into the analysis, the survivable velocities would increase. In particular, the 95th-percentile survivable velocity would increase, and, if the same process for setting design standards were repeated, the design requirements would increase perhaps beyond practical and cost-effective levels.

Table 5.2 compares the 95th-percentile impact velocities from this study with those in the 1979 CSDG and the 1989 Shanahan paper. The 95th-percentile vertical speed is higher in this study than in either of the earlier studies. The survivable horizontal velocity has increased dramatically compared to the 1979 study. While some of this increase may be assignable to differences in the studies, much of the improvement is undoubtedly real. The difference in vertical velocity between this study and the 1979 CSDG represents a 33-pct greater kinetic energy, while the kinetic energy corresponding to the horizontal velocity in this study has increased 243 pct compared to the kinetic energy in the 1979 CSDG horizontal velocity.

Table 5.2. 95th-percentile survivable impact velocity in three studies

Study	Vertical Speed (95th)	Horizontal Speed (95th)
This study - ‘04	48.4 ft/sec	93.0 ft/sec
Shanahan - ‘89	36.7 ft/sec	83.6 ft/sec
CSDG - ‘79	42.0 ft/sec	50.2 ft/sec

<u>Forward Velocity</u>

In trying to evaluate the effectiveness of the design conditions to date and also decide whether to modify them in the future, the desire is not only to quantify existing performance, but also attribute causation. Table 5.3 reports the 95th-percentile forward survivable and all mishap velocities for the four aircraft types in the study. The UH-60 shows a substantial increase of 24 ft/sec in survivable velocity over the OH-58, which also exceeds the increase of 13 ft/sec in the 95th-percentile velocity of all mishaps from the OH-58 to the UH-60. Thus, it can be concluded that the crashworthiness design requirements have been beneficial in the case of the UH-60. Even though there has apparently been an overall increase in the speed of the mishaps from the OH-58, there has been an even larger increase in the survivable velocity. This effect is also represented in the third column, which presents the 95th-percentile survivable velocity as a percentage of the 95th-percentile of all mishaps velocity. This quantity could be expressed as follows: the UH-60 is survivable in crashes that occur at velocities up to 71 pct of its 95th-percentile mishap velocity, whereas the OH-58 is only survivable crashes that occur at velocities in up to 61 pct of its 95th-percentile mishap velocity.

Table 5.3. Forward velocity survivability performance of aircraft relative to all mishaps and design condition

Aircraft	95th-%ile Survivable Forward Velocity (ft/sec)	95th-%ile All Mishaps Forward Velocity (ft/sec)	Survivable Velocity as Percent of all Mishap Velocity	%ile Survivable Velocity = to Design Condition of 27 ft/sec
CH-47	113	156	72	73
OH-58	83.5	138	61	63
UH-60	107	151	71	60
AH-64	83.2	143	58	61

The story is not quite so positive for the AH-64; although its 95th-percentile mishap velocity has increased slightly compared the OH-58, its 95th-percentile survivable velocity is just equal to the OH-58. Since the survivable data include the partially survivable events, the lack of improvement cannot be attributed solely to the vulnerability of the forward crew position. Some additional analysis that looks at the difference between results for S=1, 1+2, and 1+2+3 events might be enlightening here. The AH-64 shows a decrease in the measure of survivable velocity as a percentage of the mishap velocity, falling to 58 pct as compared to 61 pct for the OH-58.

The final column is an indicator of where each aircraft falls relative to the forward design condition. The number reported represents the percentile at which the design condition falls in that aircraft's survivable mishaps. The author has selected the slightly higher forward component velocity of the combined high angle condition (#6) for this benchmark. For this measure, a lower value is desirable, because a lower number indicates that the aircraft is out-performing the design condition by a greater margin. By this measure, the UH-60 and the AH-64 show little improvement over the OH-58.

Vertical Velocity

Both the UH-60 and the AH-64 show strong gains from the OH-58 in survivable downward velocity even though there have been large increases in each aircraft's mishap velocity relative to the OH-58. As shown in Table 5.4, the UH-60 in particular indicates an 18 ft/sec increase in the downward mishap velocity (53.6 ft/sec compared to 35.0 ft/sec for the OH-58). Despite this large increase in mishap velocity, the UH-60 remains survivable up to a velocity equivalent to 81 pct of its 95th-percentile downward velocity for all mishaps (Column 2 of Table 5.4 divided by Column 3), an improvement compared to the OH-58 at 72 pct. The AH-64 is performing even better by being survivable up to a velocity equivalent to 92 pct of its 95th-percentile downward mishap velocity.

Table 5.4. Downward velocity survivability performance of aircraft relative to all mishaps and design condition

Aircraft	95th-%ile Survivable Downward Velocity [Table 2.8] (ft/sec)	95th-%ile All Mishaps Downward Velocity [Table 2.10] (ft/sec)	Survivable Downward Velocity as Percent of 95th Percentile Downward Velocity all Mishaps	%ile Survivable velocity = to the Design Condition of 42 ft/sec
CH-47	48.0	86.8	55	92
OH-58	35.0	48.4	72	94
UH-60	53.6	66.1	81	85
AH-64	51.0	55.2	92	94

The information in the last column is quite revealing for the downward case. The reader can see first of all, that the OH-58 and aircraft like it were the aircraft studied to set the standard, as the OH-58 falls almost exactly on the design standard figure of 42 ft/sec (which is the 94th-percentile survivable velocity). The UH-60 is descending into mishaps faster than the aircraft studied for the design condition, but it is also providing improved survivability, so the design condition falls lower on the UH-60's survivable velocity curve. As reflected in the comparatively smaller increase in the vertical mishap velocity of the AH-64, 42 ft/sec still falls far up the AH-64's velocity curve. However, it should be kept in mind that for the UH-60 and the AH-64, the velocity of 42 ft/sec falls among the two to four highest velocity mishaps in the data set, and thus, the percentile figure represents an interpolation between two significantly different velocities. In other words, the percentile value is interpolated between the nearest data points that are relatively far apart, thus, the calculated value has uncertainty.

Velocity Improvement Causation

In addition to the crashworthiness design conditions, one might also consider attributing the velocity increase to rotor technology changes. However, the comparison between the OH-58D with its revised rotor system and the earlier OH-58A-C models does not support attributing the difference to the newer rotor systems. Table 5.5 shows that the OH-58D model has a markedly lower forward impact velocity compared to the OH-58A-C models, while the vertical impact velocity is virtually unchanged. The reduction in forward velocity means that the aircraft impacts with a more nearly vertical flight path, as reflected in Table 5.5 by the resultant velocity angle median. The data on the impact pitch angle indicate at most a 9-deg difference between the two models.

In his '89 paper (5), Shanahan hypothesizes that the reason that the UH-60 is impacting at higher velocities may be attributable to higher autoroational sink speeds, higher disk loading, and its lower rotor inertia. However, the comparison of the OH-58A-C models' findings to the OH-58D model's findings do not appear to support this hypothesis. The OH-58D has a higher disk loading at maximum gross weight of approximately 21 pct, and a lower rotor inertia by about 16 pct. The OH-58's AI at maximum gross weight is lower for the D model than for the A-C models, which, according to the correlation, should predict higher impact velocities for the D model than for the A-C models; however, the data indicate that the forward impact speeds related to mishaps are distinctly lower. Additional work on the OH-58 analysis is warranted.

Table 5.5. Comparison of OH-58 models

	OH-58D	**OH-58A-C**
GROUND_SPEED Mean	18.95* ft/sec	37.76* ft/sec
Forward Impact Velocity Mean	18.73 ft/sec	24.63 ft/sec
Forward Impact Velocity Median	11.05 ft/sec	13.10 ft/sec
Vertical Impact Speed Mean	16.67 ft/sec	19.23 ft/sec
Vertical Velocity (+) Mean	15.44 ft/sec	13.37 ft/sec
Vertical Velocity (+) Median	11.20 ft/sec	11.25 ft/sec
Resultant Velocity Angle Median	65.5 deg	29.0 deg
Pitch Angle Median	4.50 deg	3.00 deg
Pitch Angle Mean	7.31 deg	-1.92 deg
Autorotation Index at max. GW	49.51	76.88

* Indicates that the difference is statistically significant.

Angles of Impact

The data on angles of impact indicate a trend toward a wider spread of angles. The increase in angle diversity is reflected by a decrease in the fraction of impacts that occur within a small angle of the nominal orientation. As can be seen in Table 5.1, the CSDG study found 90 pct of impacts occurred within 15 deg of 0 pitch angle and 80 pct occurred with 15 deg of zero roll and

zero yaw angles. Even though the CSDG study included only survivable accidents and the two more recent studies include all mishaps, comparing the information in the later two studies suggests that there is a distinct trend toward more divergent angles.

The reduction in the frequency of mishaps that occur within a tight range around the normal aircraft attitude suggests the efficacy of the landing gear in absorbing its share of the crash so that the crash energy will be reduced. If this trend continues in future mishaps, designers will need to revise their strategies for energy absorption to take more energy out with techniques which are less sensitive to attitude than the landing gear. Techniques such as energy-absorbing subfloors are less attitude-sensitive. Certainly, the vertical impact condition (Number 3 in Table 4.1) should be reviewed with consideration to opening up the roll and pitch angle requirements another 5 deg in each direction.

Inverted Crashes

With 14 pct of all crashes based on an upward velocity component, inverted impacts are a significant subset of the serious mishaps. In past investigations, many, if not all, of these events would have been discarded either because they were non-survivable or because they resulted from mid-air collisions. However, the analysis in this study finds that approximately 49 pct (See Table 3.5) of inverted events are survivable. The OH-58 delivers some survivability in 51 pct of its inverted impacts, similar to the H-47, although the H-47 has a subset of only seven inverted events. The two newer aircraft designs show mixed results here. The AH-64, with a population of only 7 events, was survivable in 4 of those events, or 57 pct, whereas the UH-60 was survivable in only 36 pct of its 14 inverted mishaps. Although it might be expected that there would be a significant improvement in the survivability of these newer designs with their superior crashworthiness, it is evident from Table 4.6 that these newer aircraft are also crashing at higher upward velocities, and that simple survival percentages are not revealing the entire story. Looking at the velocities of the survivable inverted crashes, it may be seen that the UH-60 experienced a survivable inverted crash at a velocity as high as 39 ft/sec, compared to 36 ft/sec for the most-severe survivable inverted crash in the OH-58. The AH-64 had a survivable inverted crash at 72 ft/sec. The velocities for the non-survivable crashes suggest why the percentage of survivable crashes may be down, whereas the survivable velocity is up for the new aircraft. The OH-58's highest non-survivable inverted crash velocity was 97 ft/sec, whereas the UH-60's corresponding crash velocity (See Table 4.6) was 183 ft/sec and the AH-64's was 267 ft/sec.

Considering that the percentage of mishaps that correspond to some of the existing design criteria are less than 10 pct, and that 14 pct of impacts are inverted, the inverted impact condition should be considered as a possible design scenario.

Mission Phases

While there is no earlier study information with which these statistics can be compared, the data provide some insight into the emergency scenario. The mission phase where the crash event occurs is dominated by emergency autorotation (23 pct), validating the notion that rotorcraft aircrews often have time to evaluate and respond to emergency scenarios. The second most common mission phase is landing, once again indicative of aircrew response to indications of emergency situations either reported directly by the instruments or indirectly by unusual noises or vibrations. Hover is the third most frequent mission phase, and it is believed that this reflects the high pilot workload of combining hover with other tasks such as observation or weapons firing. Many of these accidents occur as unperceived drift is terminated by contact with trees or other obstacles. If it were not for this substantial number of accidents that occur out of hover, the mean and median forward velocities at impact would be substantially higher. These events occurring out of hover also validate the pure vertical design condition (Item Number 3 in Table 4.1).

No strong trend reveals itself in the mission phase prior to the crash event. Cruise constitutes 15 pct, but 9 other phases occur in 5 pct or more of the mishaps. The next two after cruise are descent and approach at 12 pct each.

The only category specifically addressing training is “training autorotation”; however, having read all of the summaries, it is the analyst’s perception that training activities are referred to far more often than the 4 pct reflected by training autorotation.

Surfaces and Obstacles

While sod continues to be far and away the most common identified impact surface (217 sod, 22 prepared), trees are what catches the data analyst’s attention. In reading through 500-plus summaries, references to trees occur with great frequency. Fully 121 of the included 318 events used in the study involved trees as landing site obstacles. As described in Section 4 on scenarios, the one change that the analysts would contemplate recommending is to change the “longitudinal impact into a vertical surface” category to “longitudinal impact into a pole or tree trunk”. While the database does not subdivide the tree contacts down into which part of the tree was impacted, it seems a reasonable assumption that more tree trunks and heavy limbs were impacted than vertical surfaces. Only 5 buildings and 24 “other” objects were reported as impact obstacles. It is possible that some additional information about the interaction between the mishap helicopters and trees could be extracted from the fuselage damage table within the database.

Aircraft Design

While it is disappointing that attempts to build a regression model around aircraft performance or design parameters and crash kinematics variables were not successful, the study did have two significant findings in this area.

First, the change in rotor system from the OH-58A-C to the OH-58D offers a rare opportunity in the crash analysis field to study the result of changing only one substantial aspect of an aircraft design. As such, the dramatic change in the average forward impact velocity, combined with a rather minimal change in the vertical impact velocity calls for additional study. The change to the OH-58’s rotor system also offers the possibility of separating out the contributions of crashworthiness design and the higher-performance rotor systems in both the UH-60 and AH-64, when comparing their mishap behavior with the earlier systems, upon which the crashworthiness standards were based.

Second, the finding of a correlation between the AI and both the forward and vertical impact velocities indicates that the AI captures some aspect of the aircraft behavior that may be exploited for predictive design work. The utility of AI as a design tool depends on the designer's flexibility to manipulate the component variables to raise the AI and still meet the other flight performance requirements for the design.

Recommendations

The following recommendations are made for actions:

- Consider creating a design condition for inverted impacts.
- For the vertical impact condition, consider expanding the angle requirement for pitch and roll.

The following recommendations are made for further study:

- Set up a methodology to evaluate the performance of each aircraft type against the design conditions as stated in Table 4.1. Use a method similar to that discussed in Section 4, but applied to each aircraft. For the conditions where velocities are identified, look at the percentile where that velocity falls for each level of survivability in a given aircraft's data set of mishaps. Where a range of angles is not stated, agree upon an angle tolerance.
- Investigate in greater detail the relationship between tree impacts and damage to the fuselage. Attempt to quantify if the loss of occupiable volume is substantial in tree impacts.
- Investigate the types and severity of injuries in tree-impact mishaps contrasted with non-tree impacts.
- Based on the outcome of the previous two items, consider revising the longitudinal impact scenario to an impact into a pole or tree, rather than a vertical surface.
- Continue to investigate the relationship between Autorotation Index and impact velocity components.
- Investigate what further information regarding (i.e., more general than crash) survivability can be extracted from the OH-58A-C versus OH-58D comparison.
- Future studies of this type would benefit from the inclusion of a flight dynamicist or pilot on the team; ideally, this would be a person well versed in both aspects of helicopters.
- Study the inverted crash mishaps with the intent of creating a proposal for an inverted impact design scenario. Consider creating a definition for an inverted impact, and then reviewing the number of events and their outcome within the limits of that definition.

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2. All Ac Cum Vel: 4 Ac Cum Forw Data
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4. All Ac Cum Vel: 4 Ac Cum Forw Data
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13. All Ac Angle Charts PR&Y: All Ac Yaw hist data
14. Comb Angle Cum Charts: Comb Pitch Cum data
15. Comb Angle Cum Charts: Comb Roll Cum data
16. Comb Angle Cum Charts: Comb Yaw Cum data
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23. All Ac Cum Vel: 4Ac Cum Lat S=1&2 data
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28. All Ac Cum Speed: Grd Spd Plot data S= 1 & 2
29. All Ac Cum Speed: V Spd Plot data S= 1 -3
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