Technology and Military Rotorcraft Mishaps[1]

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IDA contributed to and helped the Department of Defense prepare for a briefing to the House and Senate Committees on Armed Services about technologies that could potentially prevent military helicopter crashes and related fatalities. This paper summarizes the methods and some of the outcomes of that work. The result is an integrated perspective on the causes and numbers of rotorcraft mishaps, the effectiveness of technologies to reduce future mishaps, and the costs and benefits associated with technology application.

Technologies should be applied earlier in a rotorcraft's life cycle to maximize the potential to save both rotorcraft and lives.

Introduction

The National Defense Authorization Act for Fiscal Year 2017 required the Secretary of Defense to brief the House and Senate Committees on Armed Services about technologies with the potential to prevent

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military helicopter destruction and related fatalities. A team of IDA researchers prepared input for the briefing by identifying and ranking potential technologies, performing a cost-benefit assessment, and looking at casualty rates based on location within the helicopter—cockpit or cabin. The work was informed by research on this topic conducted over the past 20 years (Allen et al. 2002; Mapes 2008; Couch and Lindell 2010; Bolukbasi et al. 2011; Greer et al. 2014; Labun 2014) and by recent interviews with personnel from government research organizations and the rotorcraft industry.

Counting Mishaps by Aircraft Type

Aircraft mishaps are grouped into discrete classes based on property damage and casualty levels. Table 1 lists current Department of Defense (DoD) definitions of mishap severity by class.

Table 1. Aircraft Mishap Classes Defined

	Property Damage		Fatality/Injury
Class A	Greater than $2,000,000 ($1,000,000 prior to 2009) and/or aircraft destroyed	*or*	Fatality or permanent total disability
Class B	$500,000–$2,000,000	*or*	Permanent partial disability or 3 or more persons hospitalized as inpatients
Class C	$50,000–$500,000	*or*	Nonfatal injury resulting in loss of time from work beyond the day or shift when injury occurred
Class D	$20,000–$50,000	*or*	Recordable injury or illness not otherwise classified as Class A, B, or C

Source: DoD (2011, 45).

In addition to being sorted by mishap class, aviation mishaps are also subcategorized in terms of flight, flight related, and ground operations (DoD 2011, 29) as follows:

- *Flight mishap* is when flight of a DoD aircraft is intended and reportable damage occurs to the aircraft.
- *Flight-related mishap* is when flight of a DoD aircraft is intended and reportable damage to the aircraft does not occur, but a fatality, reportable injury, or other reportable property damage does occur.
- *Ground operations mishap* is when flight of a DoD aircraft is not intended and a fatality, reportable injury, or reportable damage to the aircraft occurs.

The flight mishap is the largest contributor to Class A mishaps—the focus of our work. To obtain accurate counts, we collected data on actual mishaps for the current military rotorcraft of interest. Although the congressional language called for a study on “helicopter” crashes, we expanded the analysis to include CV-22 and MV-22 tilt-rotor vertical takeoff and landing aircraft because the causes of their mishaps were similar to those of helicopters. To make this clear to readers, the term rotorcraft was used to highlight the inclusion of aircraft beyond helicopters. Excluded from our counts were mishaps that occurred in combat locations when the cause was hostile fire, and, in some cases, when the cause was uncertain. We included a small number of incidents as Class A mishaps that the military did not. Although our mishap counts varied somewhat from official military reporting, the deviations were small and did not affect our conclusions. The number of mishaps that would occur beyond 2017 (the cutoff date for data collection) were based on projections of the future rotorcraft fleet.

Estimating Losses of Rotorcraft and Lives

We estimated the numbers of destroyed aircraft and fatalities expected over the remaining service life for current and planned fleets of military rotorcraft. The primary sources were the latest available 30-year service forecasts (though 2047) of the U.S. Navy and U.S. Army. Corresponding forecasts for the U.S. Air Force fleet were based on current inventory, age, and open-source replacement plans.

We used forecasts of annual flying hours (FH) per total active inventory (TAI) for each rotorcraft to show the FH remaining over time, starting from 2017. The FH remaining are one of the key inputs into predicting the number of rotorcraft that will suffer Class A mishaps.

The total expected FH remaining for a rotorcraft's service life was used to determine the baseline number of future Class A mishaps:

1. *Conduct a least squares regression analysis with the historical Class A mishaps to generate an exponential curve fit, as is the generally observed trend (Mooz, 1976; Allen 2002; U.S. Air Force 2018). This yielded factors for Class A and B mishaps that we used to project the remaining values as a function of remaining FH.*

2. *Generate a linear fit to the current cumulative Class A mishap rate. This generally yielded the maximum remaining values as a function of remaining FH. The safety community defines aviation mishap rate as the number of mishaps per 100,000 FH.*

3. *Calculate the average results of these two approaches. This yielded the baseline number of Class A mishaps over time for the currently fielded and planned rotorcraft.*

This three-step approach provided reasonable values for total remaining Class A mishaps while reducing issues that arise due to limited data with one of the first two steps alone. We then projected the number of Class A mishaps remaining over time until retirement, which is illustrated in Figure 1. The figure shows that technologies should be applied earlier in a rotorcraft's life cycle to maximize the potential to save both rotorcraft and lives from Class A mishaps.

The baseline remaining destroyed rotorcraft and personnel fatalities plus permanent total disabilities were projected using the historical ratios to the Class A mishaps for each individual rotorcraft. For a few of the rotorcraft, the historical ratios are adjusted slightly to fit the typical range of values observed.

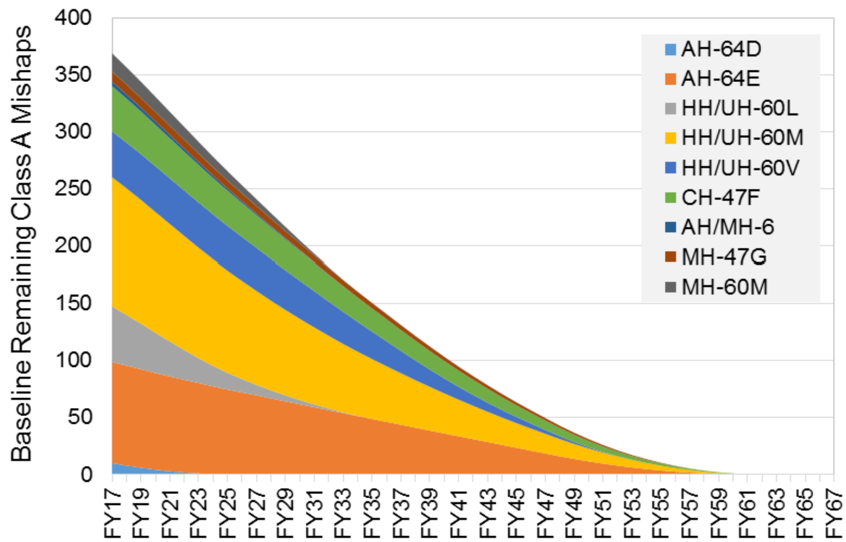

Figure 1. Projected Class A Mishaps Remaining Over Time for U.S. Army Rotorcraft

Selecting Promising Technologies to Assess

We considered technologies ranging from early development concepts to available products that could potentially reduce the future Class A mishap rate and associated fatalities in rotorcraft. In determining a list of technologies, we used DoD assessments of the underlying causes of the most serious Class A mishaps in rotorcraft in the current fleet, information drawn from a literature survey, and extensive discussions with industry and government technology experts. We relied particularly on a study by Stevens and Vreeken (2014). Although the study focused predominantly on civilian rotorcraft, it looked broadly at technologies, which were also applicable to military systems.

The assumption that types and distribution of mishaps in the past will be the same in the future combined with the predicted number of future mishaps allowed us to estimate the number of mishaps a technology could avoid. We selected five technologies predicted to have significant impact on the number of future mishaps.

For each technology, two levels of capability were envisioned:

1. *Robust level* represented the most complete and capable version of the technology and had the highest development costs.

2. *Limited level* consisted of only the basic aspects of the technology, but had lower development and installation costs.

The research team was made up of pilots and engineers with expertise in aircraft technology development and aviation safety equipment. Each of six members of the team independently reviewed nearly 400 Class A mishaps from the last several decades and assigned a mishap avoidance fraction (MAF) for each technology at each technology level. An MAF of 0 indicated that the technology would have no effect on the mishap and an MAF of 1 indicated that the technology would have kept the mishap from occurring. Taking the average of each analyst's MAF for each mishap, we estimated total MAF for each rotorcraft type and technology. Figure 2 shows the MAF distribution of technology impacts for a single rotorcraft type as evaluated by the six team members.

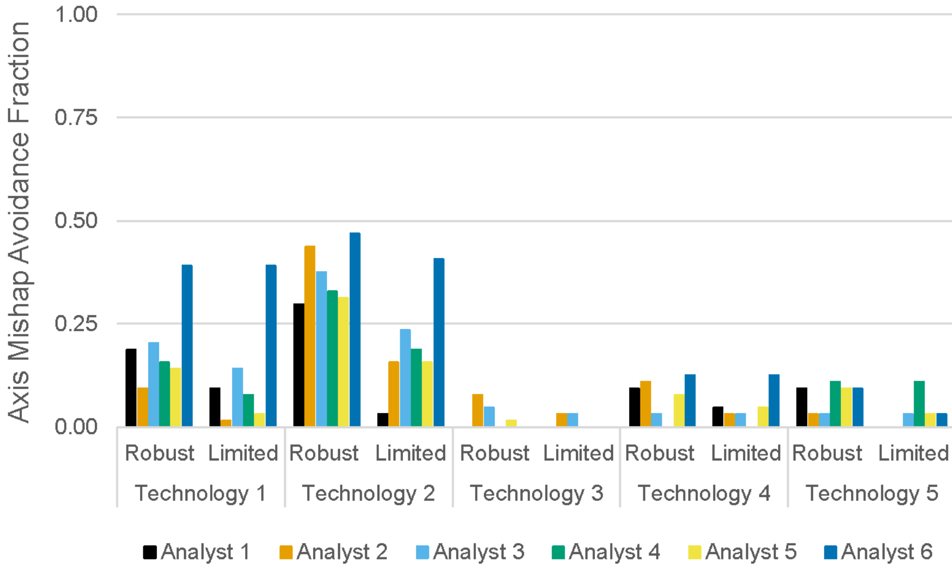

Figure 2. Example Distribution of MAF Scoring for a Single Rotorcraft Type

The final aspect of identifying the most promising technologies was the cost of developing, acquiring, and deploying each technology across the DoD fleet. We used data on existing systems that were analogous to the technologies selected to estimate these costs. The cost of fielding a technology had two main components: acquisition (cost from development to installation to procure the system) and integration (direct and indirect cost of integrating the system into the fleet of rotorcraft).

Our estimates of the number of mishaps a technology could avoid and of the cost of acquisition and integration (A&I) of that technology helped us in technology selection. These estimates were also used for the cost-benefit analysis.

Cost-Benefit Analysis

We adopted a cost avoidance model for the cost-benefit analysis. To calculate the cost avoidance for each technology, we determined savings associated with mishaps avoided as a consequence of the technology and subtracted the cost of acquiring and integrating the technology:

$$\textit{Cost Avoidance} = \left(\sum \textit{Expected Cost Without Technology} \times \textit{Mishap Avoidance Fraction}\right) - \textit{A\&I Costs},$$

where:

Expected Cost Without Technology = monetized value of anticipated fatalities, permanent total disabilities, destroyed rotorcraft, and rotorcraft damage for current equipment

Mishap Avoidance Fraction = the proportion of mishaps that will not occur due to the inclusion of technology

A&I Cost = combined costs of acquiring and installing the technology

Expected Cost Without Technology

Costs of fatalities and permanent total disability (PTDs) are major costs that the technologies assessed could potentially avoid. For cost of a fatality, we used Value of Statistical Life (VSL). According to Department of Transportation (DOT) guidance, VSL was $10.2 million in fiscal year (FY) 2017 dollars (DOT 2016, 10). PTD cost was based on the severity of an injury on the six-level Maximum Abbreviated Injury Scale (MAIS). We assumed that a PTD would be roughly equivalent to an injury of MAIS level 4 (Severe). DOT guidance specifies a disutility factor of 0.266 for MAIS level 4 injuries (DOT 2016, 10). Therefore, we estimated the cost of a PTD at $2.7 million in FY 2017 dollars (0.266 × $10.2 million). (Note that PTDs are much less common than fatalities when it comes to rotorcraft mishaps, so the results of our research are relatively unchanged for PTD values ranging from $1 million to $5 million.)

Mishap Avoidance Savings

Mishap Avoidance Factor represents the fraction of expected mishaps that will not occur because of the installation of one of the relevant technologies. It was used to determine savings for each technology under consideration for each rotorcraft type studied as follows:

Gross Savings = Expected Cost Without Technology × Mishap Avoidance Factor

Acquisition and Integration Costs

To calculate net savings, and cost avoidance, we deducted A&I costs estimated when selecting the technologies from the gross savings associated with a rotorcraft fleet upgraded with a relevant technology.

While acquisition costs apply to each rotorcraft in the fleet to be modified, integration costs apply only once for each rotorcraft type that uses the technology. Thus,

Total A&I Cost = (Acquisition Cost per Unit × Number of Rotorcraft in Fleet)
+ Integration Cost per Rotorcraft Type.

We generated a graph like the one in Figure 3 for each rotorcraft as a way to communicate the impact that technology can have on cost, lost rotorcraft, and lost lives. Each axis represents a unique aspect of the rotorcraft's mishap future. The vertical axis is the sum of the costs of damaged rotorcraft, destroyed rotorcraft, fatalities, and PTDs. The right side of the horizontal axis represents total Class A mishaps; the left side, total fatalities and PTDs. The estimated change in total costs after a technology is integrated are plotted against the baseline rotorcraft without new technology (dashed red line).

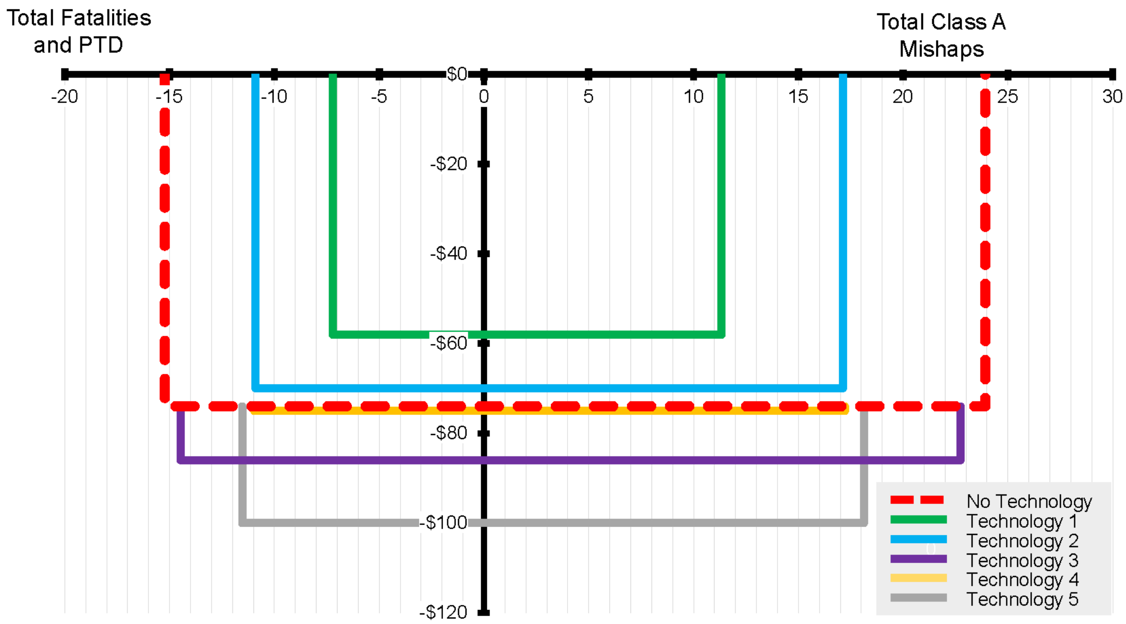

Figure 3. Impact of Technologies on Costs, Lives Lost, and Rotorcraft Lost

For the rotorcraft represented in Figure 3, Technology #1 appears to be the best choice to improve safety and reduce overall costs. The expected costs are lower ($75 million without technology and $60 million with technology), the number of Class A mishaps is significantly lower (24 without technology and 11 with technology), and the number of fatalities/PTDs is down (15 without technology and 7 with technology). Technology #3 is shown to have little impact on total Class A Mishap or fatalities/PTDs (1 of each avoided), and costs approximately $20 million more no technology.

Costs and fatalities avoided through any technology is linked to the predicted number of mishaps over the remaining life of the rotorcraft. As previously stated, the most benefit is gained when a technology is incorporated early because the number of mishaps affected decreases as rotorcraft move through their service lives.

Cost Avoidance

Given the foregoing analyses of mishap numbers, costs, and other factors, we calculated cost avoidance for each technology in each rotorcraft type in each military department. Our calculations were based on the following assumptions (costs in FY 2017 dollars):

1. The value of capability lost from a rotorcraft destroyed in a Class A mishap is equivalent to the rotorcraft's average procurement unit cost.

2. The average cost of damage to a rotorcraft that is involved in a Class A mishap but not destroyed is equivalent to 15 percent of the rotorcraft's average procurement unit cost (DoD 2011, 19).
3. Incremental operating and support costs for the technologies are insignificant.
4. Acquisition and integration (A&I) costs are the same for each technology in all rotorcraft types.
5. DOT's VSL value of $10.2 million is appropriate for the cost of a fatality.
6. An MAIS level 4 (Severe) injury is a reasonable proxy for a permanent disabilities.
7. DOT's value of $2.7 million is a reasonable proxy for the cost of an MAIS level 4 (Severe) injury.

Casualty Rates for Occupants in Different Areas of Rotorcraft

The final topic of interest was an analysis of casualty rates for persons in the cockpit versus those in the cabin. Understanding why some persons survived when others did not is crucial to understanding differences between cockpit and cabin safety. Mishaps that are survivable are of the most interest. Incidents where everyone perishes or no one perishes are of less interest when assessing safety equipment differences between the cockit and the cabin since the likelihood of changing outcomes for the occupants is unlikely for the former and not applicable for the latter.

To enable a consistent comparison, the number of people in a rotorcraft during the mishap had to found. Two people are always in the cockpit of a rotorcraft, but the number of people in the cabin varies from 0 to 50, depending on the type of rotorcraft. Again, we referred to mishap reports for counts of the number of people on board during survivable mishaps and the number of fatalities/PTDs for those in the cockpit and the cabin, respectively. This task was sometimes difficult as the reporting of the number of persons in the cabin was not always consistent between different portions of the mishap reports.

Use of safety equipment, primarily seats and restraints, is another consideration in determining casualty rates. In all cases of survivable mishaps, reports indicated the pilots were seated in crash-attenuated seats restrained by a five-point harness. But we found that the military departments do not routinely indicate whether a person in the cabin was seated and wearing a seat belt at the time of the mishap. This lack of detail in the mishap reports made it impossible to assess the differences in safety equipment, including the effect of having improved crashworthy seats installed in the cabin of some newer rotorcraft.

Summary

IDA-developed methods were used to estimate the number of future rotorcraft mishaps based on past mishap rates and remaining flight hours. The results of these methods provided a defendable basis by which the cost-benefit advantages of new technologies could be evaluated in reducing mishaps. Our findings indicate the maximum avoidance of cost and fatality/PTD occurs when promising technologies that enhance safety are incorporated as early as possible in the rotorcraft's life cycle. Better recordkeeping of the use and nonuse of cabin safety-related equipment, primarily seats and restraints, would enable future assessments of relative casualty rates for occupants in different parts of rotorcraft.

References

Allen, T. L., G. A. Corliss, J. A. Schwartz, and J. W. Stahl. 2002. *Assessment of Aviation Safety Concepts for Helicopters*. IDA Paper P-3671.

Bolukbasi, A., J. Crocco, C. Clarke, E. Fasanella, K. Jackson, P. Keary, L. Labun, P. Mapes, J. McEntire, J. Pellettiere, B. Pilati, F. Rumph, J. Schuck, M. Schultz, M. Smith, and D. Vasquez. 2011. "Full Spectrum Crashworthiness Criteria for Rotorcraft." RDECOM TR 12-D-12.

Couch, M. A., and D. Lindell. 2010. "Study on Rotorcraft Safety and Survivability." Presented at the American Helicopter Society 66th Annual Forum. https://apps.dtic.mil/sti/pdfs/ADA547531.pdf.

Department of Defense (DoD). 2011. Department of Defense Instruction 6055.07: Mishap Notification, Investigation, Reporting, and Record Keeping. https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/605507p.pdf.

Department of Transportation (DOT). 2016. "Guidance on Treatment of the Economic Value of a Statistical Life (VSL) in U.S. Department of Transportation Analysis – 2016 Adjustment." Memorandum (August 8). https://www.transportation.gov/sites/dot.gov/files/docs/2016 Revised Value of a Statistical Life Guidance.pdf.

Greer, W., A. O. Gallo, B. R. Harmon, B. C. Prindle, J. A. Schwartz, J. Silva, J. W. Stahl, and R. V. Uy. 2014. *Mishap Analysis for Brownout Rotorcraft Enhancement System (BORES) Analysis of Alternatives (AoA)*. IDA Paper P-5206.

Labun, L. 2014. "Rotorcraft Crash Mishap Analysis." Safe, Inc. RDECOM TR 09-D-45.

Mapes, P. B. 2008. "DoD Helicopter Mishaps FY 85-05: Findings and Recommendations." Defense Safety Oversight Council. OSD 09-S-1351.

Mooz, W. E. 1976. *A Second Look at Relationships for Estimating Peacetime Rotorcraft Attrition*. RAND Report R-1840-PR.

Stevens, J. M. G. F., and J. Vreeken. 2014. "The Potential of Technologies to Mitigate Helicopter Accident Factors—An EHEST Study." National Aerospace Laboratory NLR. NLR-TP-2014-311. https://www.easa.europa.eu/sites/default/files/dfu/NLR-TP-2014-311.pdf.

U.S. Air Force 2018. "Financial Management: US Air Force Cost and Planning Factors." AFI 65-503.

About the Authors

This paper is a great example of collaboration across divisions of IDA's Systems and Analyses Center.

Christopher Martin, Assistant Director of the Science and Technology Division, holds a master's degree in aerospace engineering from University of California, Los Angeles. This marks the first time that Chris has been recognized for his contributions to a Welch Award–nominated publication.

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