IDA | RESEARCH NOTES

WELCH AWARD 2020

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IDA operates three Federally Funded Research and Development Centers (FFRDCs) that answer the most challenging U.S. security and science policy questions with objective analysis leveraging extraordinary scientific, technical, and analytic expertise.

The articles in this issue of *IDA Research Notes* were written by researchers affiliated with two of IDA's three FFRDCs: the Systems and Analysis Center and the Science and Technology Policy Institute. The relevant directors, named below, would be happy to answer your questions about the topics discussed in these articles as well as other topics related to their work.

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The Larry D. Welch Award is named in honor of former IDA president and U.S. Air Force (USAF) Chief of Staff, General Larry D. Welch, USAF (retired). The award recognizes IDA researchers who exemplify General Welch's high standards of analytic excellence through their external publication in peer-reviewed journals or other professional publications, including books and monographs.

This issue of *IDA Research Notes* is dedicated to the nominees of the 2020 Larry D. Welch Award for best external publication. The articles in this issue are summaries derived from the best of the publications nominated this year—the winner and finalists. Citations for those publications, as well as other noteworthy publications nominated this year, are provided below, along with a link where available.[1] Authors whose names appear in bold type have current or former affiliations with IDA as researchers or consultants.

Winner

The paper recognized this year as the best example of high-quality, relevant research published in the open literature is "Characterizing the Orbital Debris Environment Using Satellite Perturbation Anomaly Data," by Operational Evaluation Division (OED) researchers **Joel Williamsen** and **Daniel Pechkis**, Science and Technology Policy Institute (STPI) researcher **Asha Balakrishnan**, and System Evaluation Division (SED) researcher **Stephen Ouellette**. Their paper was published in *Conference Proceedings of the International Orbital Debris Conference*, December 2019 (https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6065.pdf).

The paper describes a new and original concept developed by the IDA authors. NASA has identified untracked orbital debris as one of the most serious threats to satellites in low Earth orbit, where some 20,000 commercial communications and web services satellites are expected to reside in coming years. The concept involves translating observed perturbations in satellite orbits, observed through GPS and communications links, to corresponding orbital debris characteristics, potentially filling an information void in the understanding of the low-Earth-orbit debris environment that affects satellite design. The paper also uses NASA data—developed with IDA's help in government-sponsored projects over the past decade—to show a potential over-estimate of orbital debris risk based on overly conservative orbital debris mass predictions.

This is the first Welch Award–winning paper with authors from three different IDA research groups. All the authors are experts in space assessments, but it was the synergy of their expertise that led to this new concept for predicting space debris. Such collaboration is a key element of IDA's success in addressing the most challenging sponsor problems.

[1] IDA assumes no responsibility for the persistence of URLs for external and third-party internet websites referred to in this publication. Further, IDA does not guarantee the accuracy or appropriateness of these websites' content now or in the future.

Finalists

The following nominated publications were finalists in the voting process. These publications illustrate the diversity of IDA expertise and reflect well upon the authors as well as IDA. Authors whose names appear in bold type have current or former affiliations with IDA as researchers, members of division management, or consultants.

"Building a 21st Century Defense Acquisition Workforce," *War on the Rocks*, May 6, 2019, by Strategy, Forces and Resources Division (SFRD) senior fellow **Peter Levine** (https://warontherocks.com/2019/05/building-a-21st-century-defense-acquisition-workforce/).

"In Search of a 21st Century Joint Warfighting Concept," *War on the Rocks*, September 19, 2019, by Joint Advanced Warfighting Division (JAWD) researchers **Tom Greenwood** and **Pat Savage** (https://warontherocks.com/2019/09/in-search-of-a-21st-century-joint-warfighting-concept/).

"Methodologies to Assess the Influence and Cost Benefit of Technology on Military Rotorcraft," *Proceedings of the 75th Annual Forum and Technology Display, Vertical Flight Society*, 2019, by Science and Technology Division (STD) assistant director **Christopher Martin**, JAWD adjunctC researcher **Thomas Allen**, OED researcher **Mark Couch**, Cost Analysis and Research Division (CARD) researcher **Jack Law**, and SED researchers **Joshua Schwartz** and **Paul Jones** (https://vtol.org/store/product/methodologies-to-assess-the-influence-and-cost-benefit-of-technology-on-vertical-lift-aircraft-mishaps-and-fatalities-14557.cfm). This paper is another example of collaboration across different IDA research group.

"Optimizing the Purchases of Military Air-to-Ground Weapons," *Military Operations Research* 24, no. 4 (2019): 37–52, by CARD Deputy Director **Matthew Goldberg** and external coauthor David Goldberg (https://www.jstor.org/stable/26853512).

"U.S. Training of African Forces and Military Assistance, 1997–2017: Security versus Human Rights in Principal-Agent Relations," *African Security*, 2018, by Intelligence Analyses Division (IAD) researcher **Stephanie Burchard** and external coauthor Stephen Burgess (https://doi.org/10.1080/19392206.2018.1560969).

"User-Oriented Independent Analysis of the Toxic Load Model's Ability to Predict the Effects of Time-Varying Toxic Inhalation Exposures," *Regulatory Toxicology and Pharmacology* 106 (August 2019): 27–42, by SED researchers **Alexander Slawik**, **Nathan Platt**, and **Jeffry Urban** (https://doi.org/10.1016/j.yrtph.2019.04.003).

"What Is Agreed Competition in Cyberspace?" *Lawfare*, February 19, 2019, by Information Technology and Systems Division (ITSD) researcher **Michael Fischerkeller** and external coauthor Richard Harknett (https://www.lawfareblog.com/what-agreed-competition-cyberspace).

Noteworthy

The Welch Award Selection Committee named four other nominated publications as being worthy of note.

"Active Denial Technology Computational Human Effects End-to-End Hypermodel (ADT CHEETEH)," *Human Factors and Mechanical Engineering for Defense and Safety* 3, no. 13 (August 20, 2019), by STD researchers **Shelley Cazares**, **Jeffrey Snyder**, **James Belanich**, **John Biddle**, **Allyson Buytendyk**, and **Kelly O'Connor** and STD assistant director **Stacy Teng** (https://doi.org/10.1007/s41314-019-0023-7).

"Quantifying the Year-by-Year Cost Uncertainty of Major Defense Programs," *Proceedings of the Sixteenth Annual Acquisition Research Symposium*, Volume 2 (April 30, 2019): 153–169, by CARD researcher **David Tate** and SFRD adjunct researcher **Michael Guggisberg** (http://hdl.handle.net/10945/62910).

"Phasor Field Waves: A Mathematical Treatment," *Optics Express* 27, no. 20 (2019): 27500–27506, by STD researcher **Jeremy Teichman** (https://doi.org/10.1364/OE.27.027500).

"The Weight of the Shadow of the Past: The Organizational Culture of the Iraqi Army, 1921–2003," in *The Culture of Military Organizations*, Part 2, Chapter 12 (Cambridge University Press, 2019): 272–298, edited by Peter Mansoor and Williamson Murray, by JAWD deputy director **Kevin Woods** (https://doi.org/10.1017/9781108622752.013).

Using Satellite Movements to Predict Orbital Debris Risk[1]

Joel E. Williamsen, Daniel L. Pechkis, Asha Balakrishnan, and Stephen M. Ouellette

Untracked orbital debris poses a risk to the growing number of satellites. The authors demonstrate how debris smaller than the width of a pencil can be detected by examining changes in a satellite's attitude.

Introduction

Untracked orbital debris is a serious risk to the survivability of satellites, particularly those in low Earth orbit (LEO). Acknowledging the growing threat such debris poses to space operations, U.S. National Space Traffic Management Policy (also known as Space Policy Directive-3) calls for "advancing the S&T [science and technology] of critical SSA [space situational awareness] inputs such as observational data, algorithms, and models necessary to improve SSA capabilities" (National Space Traffic Management Policy 2018, 28970). Guidelines for doing so should minimize SSA deficiencies "in regions with limited sensor availability and sensitivity in detection of small debris" (National Space Traffic Management Policy 2018, 28971).

Some new method of gathering data for predicting satellite impacts with debris of all sizes is needed to calibrate existing NASA orbital debris models.

Existing NASA models for characterizing small orbital debris in LEO depends on interpolating between impact counts from short duration Shuttle missions (under 1 millimeter in size) and radar data (above 3 millimeter in size), leaving a critical gap in predicting impact with particles 1–3 millimeters in size. This gap is small but important because this size regime can kill a small satellite when impacting at orbital velocities, and the number of satellites in LEO is expected to increase dramatically in the next decade (NewSpace 2018). NASA's Orbital Debris Engineering Model (ORDEM) 3.0 indicates that satellites in LEO by 2029 will face potential collision with more than 16,000 pieces of orbital debris of 1 millimeter or larger each year. Further, many of those satellites will be in orbits where debris under 1 centimeter in size is both untrackable and dangerous.

Survival of new satellite constellations in LEO will depend on the accuracy of debris prediction models. Some new method of gathering data for predicting satellite impacts with debris of all sizes is needed to calibrate existing NASA orbital debris models. This paper outlines a technique for using 1–20 meters changes in satellite mean altitude to calculate the size of small, untrackable orbital debris particles that impact satellites.

Converting Satellite Perturbations into Orbital Debris Environment Predictions

A 2017 technical study for NASA compared predictions of satellite failures from impact with debris against observations of satellite anomalies from impact with

[1] Based on J. E. Williamsen, D. L. Pechkis, A. Balakrishnan, and S. M. Ouellette, "Characterizing the Orbital Debris Environment Using Satellite Perturbation Anomaly Data," *Conference Proceedings of the International Orbital Debris Conference*, December 2019, https://www.hou.usra.edu/meetings/orbitaldebris2019/orbital2019paper/pdf/6065.pdf.

debris (Squire et al. 2017). The failure predictions and anomaly observations were limited to sudden leaks in pressurized batteries and propulsion tanks—failures that were most likely to be caused by sudden orbital debris impact. Between 8 and 11 failures were predicted, but only two anomalies were actually reported. This indicates either the model is overpredicting failures or satellite owner-operators are underreporting them. The range of orbital debris sizes causing failure varied from 1.5 to 4 millimeters—the range where the least information exists about the orbital debris environment. This implies a need for better observed data in this range.

For the same NASA study, an IDA-developed prediction technique (Williamsen and Evans 2017) was used to correlate impacts with orbital debris of various sizes to reported motion of satellites in LEO. IDA used hydrocode analyses to determine the effects of different orbital debris sizes, masses, velocities, and directionalities on plates that simulate subsequent layers in general satellite construction. (Hydrocodes model the fluid-like response of solid materials to short-duration loading from much higher velocity impact.) Using this technique, IDA established that the momentum enhancement factor (MEF) of the impacting particle varies between 1.5 and 3, depending on the structure hit. MEF relates how much the backward flow of debris material reduces the satellite's forward velocity and thus lowers the average satellite altitude. Thin structures, for example, do not react strongly to orbital debris impact because the debris tends to go through them without multiplied momentum.

Satellite mean altitude is the average of the satellite's altitudes at perigee (the portion of the orbit closest to Earth) and at apogee (the portion farthest from Earth). The change in altitude after collision for satellites in circular orbits is called the delta semi major axis (dSMA). A mathematical illustration of the magnitude of the collision's effect on dSMA follows. For this illustration, assume the satellite is in a circular Keplerian orbit (Earth at the center of the circle).

$$v^2 = (1/2)\, v_e^{\,2}\, (2/r - 1/a)\,, \tag{1}$$

where v is the orbital velocity, v_e is the escape velocity from Earth, and r and a are the spacecraft orbital radius and semi-major axis, respectively (both unitless, as a fraction of the Earth's radius, with $r = a$ for circular orbits).

Following impact with debris, a satellite enters an elliptical orbit (Earth at either end of the ellipsis) with a new mean altitude or semi-major axis. Equation 1 computes the orbital velocity for both the original circular orbit at radius r and immediately after impact, still at radius r but with the perturbed semi-major axis a. From the change in satellite velocity dV, the debris particle's mass can be calculated using equation 2:

$$m_0 \times v_0 \times MEF = M \times dV\,, \tag{2}$$

where m_0 is the debris particle's mass, v_0 is the velocity component approaching opposite to the satellite's velocity vector, MEF is the momentum enhancement factor, and M is the satellite's mass.

Table 1 correlates calculated changes in satellite altitude following impact with orbital debris to the size of the debris particle for satellites of the following sizes made of both aluminum and steel:

- Minisatellites: 150 kilograms and 1 square meter
- Microsatellites: 37 kilograms and 0.3 square meters
- Nanosatellites: 1.5 kilograms and 0.1 square meters

Table 1. Changes in Satellite Altitude Relative to Debris Particle Size

	Diameter (in millimeters) of debris causing designated dSMA upon impact with satellite						Predicted occurrences of designated dSMA per 1,000 satellites		
	Aluminum debris			Steel debris			Aluminum and steel debris combined		
dSMA (meters)	Minisatellite	Microsatellite	Nanosatellite	Minisatellite	Microsatellite	Nanosatellite	Minisatellite	Microsatellite	Nanosatellite
20	3.30	2.07	0.71	2.32	1.46	0.50	2	21	34
15	3.00	1.88	0.65	2.11	1.32	0.46	6	35	43
10	2.62	1.54	0.56	1.84	1.26	0.40	16	68	57
5	2.08	1.30	0.45	1.46	0.92	0.32	69	172	87
3	1.75	1.10	0.38	1.24	0.78	0.27	167	303	113
2	1.53	0.96	0.33	1.08	0.76	0.23	306	454	135
1	1.22	0.76	0.26	0.86	0.68	0.17	732	868	175
0.5	0.97	0.51	0.23	0.68	0.43	0.15	1,491	1,487	216

Notes: Based on impact with debris particles in near-polar circular orbit (~50% of flux) traveling 14.94 kilometers per second at an altitude of 800 kilometers. More occurrences are possible if all flux directions are considered.

The table shows that debris detectability varies with the material it is made of, the size of the satellite it impacts, and the dSMA. For example, an aluminum particle as small as 1.75 millimeters in diameter that impacts a minisatellite can be detected by observing a dSMA of 3 meters. Likewise, a steel particle as small as 1.24 millimeters can be detected based on the same dSMA in a minisatellite. A nanosatellite weighs much less than a minisatellite, so debris particles as small as 0.38 millimeters for aluminum and 0.27 millimeters for steel cause a dSMA of 3 meters.

This information, coupled with information about a satellite's exposed area and shields, allows us to compare the predicted number of orbital changes with the observed number of a given size. Table 1 also provides expected occurrences of each dSMA, as predicted using ORDEM 3.0. Given large constellations, hundreds of hits from particles of 1–3 millimeters are expected, if NASA's model is correct.

Potential Methods to Detect Satellite *Perturbations*

A variety of methods are available for determining the magnitude of vertical satellite movement (perturbations) of 1–20 meters following debris hits of 1–3 millimeters. Among them are:

- **Ground-Based Radar and Laser Ranging**: The U.S. Space Command's Space Surveillance Network contains the largest collection of LEO-observing ground-based radar. The Combined Space Operations Center uses object tracking and radar characterization data from the Space Surveillance Network to determine a space object's location and trajectory. In turn, these location and trajectory data are used in propagation models to predict orbital positions. However, the margin of error in the orbital propagation prediction with these data exceeds the small altitude change experienced by minisatellites, microsatellites, and nanosatellites when struck by millimeter-sized space debris.
- **Monitoring Satellite Crosslinks in Constellations**: Many current and planned future satellite constellations communicate first through uplinks that send information from the ground, through crosslinks, and finally through a downlink to the recipient satellite. Sudden loss of these connections or changes in the transmission antenna's pointing angle indicate a change in a satellite's position, possibly from impact with debris. However, variation in satellite guidance or response can also be the cause of the position change.
- **Monitoring Global Positioning System (GPS) Information**: Continuous monitoring of GPS information for LEO satellites is becoming a feasible way to detect sudden changes in their mean orbital altitude. Some current GPS receivers for LEO, such as General Dynamics' Viceroy-4, have positional accuracies better than 15 meters. The newer General Dynamics' Sentinel M-Code has LEO positional errors of less than 4 meters. Furthermore, studies show that 1 meter accuracy is achievable with commercial off-the-shelf signal-frequency GPS receivers for LEO, and that accuracy can be improved down to 0.3 meters using post-processed GPS orbit and clock products (Montenbruck et al. 2012, 527).

Of these methods, the most promising are monitoring a satellite's GPS position and its ability to maintain communication crosslinks with neighboring satellites in a constellation. Using reported data on internal spacecraft anomalies (failures) that accompany a rapid change in orbital position would further improve confidence in orbital debris model predictions.

Clearly, capabilities exist that can detect and resolve the magnitude of satellite movement after an orbital debris impact, which will allow more data to be gathered on the environment. The ability to make these comparisons have ramifications for satellite design and risk perception and management.

Collecting and Distributing Anomaly Data

To best address the potential risk from orbital debris, and to help improve debris models (particularly the ORDEM model), satellite owners and operators need to share data and other satellite information within a common framework. Currently, satellite owners and operators rely on the ORDEM 3.0 debris model to predict satellite anomalies or failures. Sharing anomaly data would allow for a more realistic assessment of the true debris environment.

In line with its goals to create a safer operating environment and to establish new guidelines for satellite design and operation, Space Policy Directive-3 named the Department of Commerce as administrator of an open architecture data repository. Anomaly data could be an important part of this repository. To understand how anomaly data collection and distribution can be part of an orbital debris mitigation process, consider the following roles U.S. Government agencies have in monitoring and regulating the space environment:

- The Department of Defense (DoD) owns the U.S. Government sensors that identify and track space objects.
- NASA is leading the effort to establish new guidelines for satellite design and operation through the U.S. Orbital Debris Mitigation Standard Practices. NASA also represents the United States on the Inter-Agency Debris Coordinating Committee of the United Nations. This committee coordinates space debris research between members, reviews progress of ongoing cooperative activities, and identifies debris mitigation options.
- The Federal Communications Commission (FCC) is responsible for licensing radio transmissions from satellites owned by private companies. Under rules put into effect in 2005, FCC authorization requires communication satellites that transmit to U.S. receiver systems to submit documentation on their debris mitigation strategy. A debris mitigation strategy includes plans to limit both operational debris produced and the probability that the satellite itself will become a source of debris (Sorge 2017, 2–3).
- Within the Department of Transportation, the Federal Aviation Administration (FAA) Office of Commercial Space Transportation oversees, authorizes, and regulates launches and reentries of vehicles and the operation of launch and reentry sites for the United States. The FAA's debris mitigation regulation focuses primarily on reentry debris.
- The National Oceanic and Atmospheric Administration (NOAA) issues licenses for remote sensing space systems. To obtain a license, a licensee must assess and minimize the amount of orbital debris associated with the system's disposal.

DoD and NASA are both involved in assessing the orbital debris environment; NASA leads the effort and the DoD provides satellite object data. The FCC, the FAA, and NOAA are all involved in licensing U.S. commercial satellite systems; each agency has different degrees of oversight related to orbital debris.

Current orbital debris regulations focus on plans for mitigating production of debris and for properly disposing of debris that is produced. Absent from these regulations is a requirement for satellite owners or operators to provide data that will aid in assessing the debris environment. Figure 1 illustrates how anomaly data collection and distribution would fit into the agency roles and processes for orbital debris mitigation.

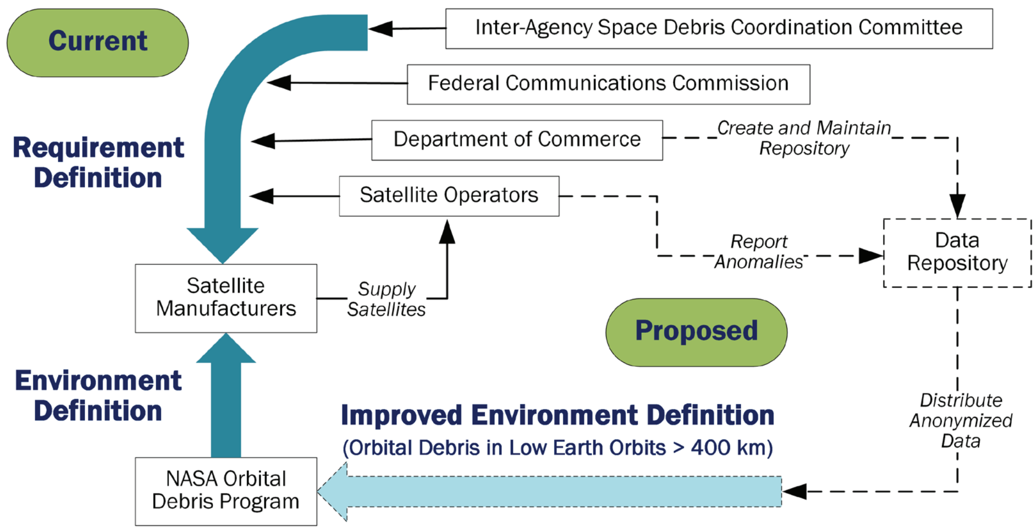

Figure 1. Relationship of Anomaly Data Collection and Distribution to Orbital Debris Mitigation

We propose that the Department of Commerce include in its data repository the location and tracking of objects and a mechanism to capture anomaly data caused by debris. Sharing anomaly data that has been tracked in a standard and consistent manner can lead to better understanding of the root causes of failures and, ultimately, to improved satellite designs.

Developing a transparent process and educating owners and operators about the benefits of submitting anomaly data to the data repository could motivate satellite owners and operators to take responsibility for fostering a safe space environment. Alternatively, the United States could make sharing anomaly data part of the mitigation portion of licensure applications or a prerequisite to receiving object catalog services. These data could be anonymized—the minimum data requirement would be satellite mass, original altitude, altitude change, and approximate time and location of impact. Satellite operators could voluntarily offer concurrent satellite information (system failures, satellite rotation, etc.) to strengthen the case for orbital debris impact as the source of the observed perturbation, and reduce uncertainties associated with the predicted orbital debris impact parameters.

Conclusion

Prior to launch, all U.S. Government agencies that operate satellites in LEO must meet requirements for assessing risks to a satellite from impact with debris smaller than 1 centimeter. The accuracy of risk assessments directly depends on the accuracy of orbital debris environment predictions. Overpredicting risk can lead to heavier satellites and higher launch costs.

NASA studies show that orbital debris 1–3 millimeters in size cannot be directly measured, but can be expected to cause serious or catastrophic damage to spacecraft in LEO, where the number of satellites is increasing rapidly. Current NASA orbital debris environment models and spacecraft assessment techniques for altitudes above 400 kilometers appear to overpredict the number of satellite impacts by a factor of 10 and the number of failures by a factor of 5. Clearly, better orbital debris environment data are needed for these altitudes to accurately predict the number of satellite impacts and failures, particularly as the use of LEO space expands.

NASA can use the technique outlined in this article to detect, validate, and improve ORDEM 3.0. Further, in line with the goals of Space Policy Directive-3, the Department of Commerce could incorporate anomaly data in its open architecture data repository to improve understanding of the orbital debris environment.

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Building a Modern Defense Acquisition Workforce[1]

Peter K. Levine

Advocates of acquisition reform have long sought changes in the civil service rules to make it easier to build the kind of workforce that the Department of Defense needs to efficiently execute the defense acquisition process. Despite a wide array of new programs and legislative authorities, little has changed. The author suggests that what is needed is a new mindset, not a new set of rules. Instead of managing civil service positions, the Department of Defense must start managing its people.

Introduction

Every year, the Department of Defense (DoD) acquisition workforce is responsible for negotiating prices, enforcing requirements, managing delivery, addressing interoperability and sustainability, and ensuring cyber and supply chain security for every item in the annual defense acquisition budget. And every year, Congress makes this already daunting process more complex by introducing acquisition legislation provisions that change the rules on types of contracts, contract audits, source selection criteria, commercial items acquisition, data rights, intellectual property, and more.

Model career paths show a rotation of individuals through a progression of assignments and training experiences to build needed skills and competencies.

[1] Based on P. Levine "Building a 21st Century Defense Acquisition Workforce," *War on the Rocks*, May 6, 2019, https://warontherocks.com/2019/05/building-a-21st-century-defense-acquisition-workforce/.

Advocates of acquisition reform have long sought changes in the civil service rules to make it easier to build the talent that the Pentagon needs to meet this challenge, but despite the wide array of legislative authorities now available, little has changed. If DoD wants to develop talented employees rather than manage them for immediate performance, they must establish a system that enables rotating future civilian leaders through a series of time-limited, career-building assignments.

Call for Civilian Personnel Reform

In 2003, the National Commission on the Public Service reported that the Federal Government was not adequately staffed to meet the demands of the 21st century (National Commission of the Public Service 2003, 1):

> Those who enter the civil service often find themselves trapped in a maze of rules and regulations that thwart their personal development and stifle their creativity. The best are underpaid, the worst, overpaid. Too many of the most talented leave the public service too early, too many of the least talented stay too long.

In 2017, a panel of the National Academy of Public Administration reached a similar conclusion. Citing Government Accountability Office findings of "serious gaps between the skills agencies needed and the skills they had on board," the panel concluded: "The country is flying blind into wicked problems, without enough pilots who know how to direct its programs onto the right routes" (Panel of the National Academy of Public Administration 2017, 14).

Almost every major study of the defense acquisition system, from the 1986 Packard Commission report[2] to the 2006 Defense Acquisition Performance Assessment, has similarly pointed to shortcomings in workforce training and expertise. Yet a 2016 survey found that the Federal Government continues to "suffer from a capability gap when it comes to hiring, training, and retaining acquisition workers" and that most of the workforce remains "unprepared or unwilling to take well-reasoned risks to exploit potential innovations or cost savings" (Grant Thornton and Professional Services Council 2016, 1). A 2017 MITRE paper stated that "the acquisition workforce lacks the experience, knowledge, and tools necessary" and "struggles to keep pace with the increasing complexity of the federal acquisitions." (Murphy and Bouffard 2017, 2).

Reviews of specialized acquisition fields have likewise identified shortfalls. A congressionally mandated panel report in 2018 said that acquisition personnel "do not receive adequate, if any, training in" management of technical data and computer software rights. The report recommended additional training and use of a cadre of subject matter experts (Government-Industry Advisory Panel on Technical Data Rights 2018, 1–2). Similarly, a 2019 report of the Defense Innovation Board found

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2 President's Blue Ribbon Commission on Defense Management, 1986, *A Quest for Excellence: Final Report to the President*.

3 Assessment Panel of the Defense Acquisition Performance Assessment Project, 2006, *Defense Acquisition Performance Assessment Report*.

that the defense human resource system fails to build needed software acquisition expertise and recommended "establishing software development as a high-visibility, high-priority career track with specialized recruiting, education, promotion, organization, incentives, and salary" (Defense Innovation Board 2019, 33).

Existing Authorities and Flexibilities

Over the last two decades, three very different administrations have proposed new, far-reaching personnel authorities to address perceived shortcomings in the federal civil service system with mixed results. The second Bush administration implemented an alternative civilian human capital system—a performance-based system called the National Security Personnel System—in DoD, which ran from 2006 to 2011. The Obama administration called for instituting expedited hiring and performance-based pay systems throughout the Federal Government. And the Trump administration has proposed eliminating the General Schedule system, making it easier to hire and fire federal employees, and "reskilling" employees in antiquated positions (Office of Management and Budget 2020, 74–76).

The problem, however, may not be a lack of authority. DoD workforce authorities now include:

- Pay-for-performance programs and increased pay caps for the acquisition workforce, the science and technology workforce, the intelligence workforce, and the cyber workforce;
- Employment authorities for highly qualified experts, science professionals, temporary and term appointments, and rotational Intergovernmental Personnel Act Program employees; and
- Expedited hiring authorities for the acquisition workforce, the scientific and engineering workforce, the financial management workforce, the weapons testing workforce, the intelligence workforce, the cybersecurity workforce, the business management workforce, and the depot maintenance workforce.

DoD has multiple programs to educate, train, and advance the civilian workforce, including leadership programs like the Defense Civilian Emerging Leader Program, the Executive Leadership Development Program, and the Defense Senior Leader Development Program. DoD also has requirements for mentoring and coaching civilian employees as well as a strategic workforce planning guide and detailed regulations for civilian career management, including competency management frameworks, career ladders, and career maps.

These broad authorities are augmented by a series of special provisions applicable to the acquisition workforce. The Defense Acquisition Workforce Improvement Act, first enacted in 1990, establishes a separate acquisition corps with its own accession, education, training, and career development requirements. Six years later, the acquisition demonstration project authorized the use of direct hiring, pay-for-performance, performance management, and other flexible management tools

(Title 10 U.S.C. § 1762). From 2008 through 2016, about $4.5 billion was deposited into the Defense Acquisition Workforce Development Fund for workforce hiring, training and development, and retention and recognition (Government Accountability Office 2017, 5).

Career Development Approaches

Why haven't these new authorities been sufficient to build the specialized skills and expertise that DoD says it needs? The final report of the Section 809 panel on streamlining and codifying acquisition laws and regulations contains a hint of an answer, arguing that DoD has taken an "unbalanced approach to professionalizing the workforce by focusing primarily on training to meet certification requirements." Instead, the report suggests the focus should be on long-range career paths that include "jobs of increasing variety, complexity, responsibility, and accountability, leading to management and leadership opportunities." To address this shortcoming, the panel recommended a new "competency model" for career development that would include qualifications gained through "a combination of education, training, and practice" (Section 809 Panel 2019, 285–286).

The panel fell short, however, when it came to explaining how its career planning vision would be implemented in practice. Congress and DoD have provided similar career planning direction on multiple occasions over the last 25 years. In fact, as a member of the staff of the Senate Armed Services Committee in 2010, I helped draft a legislative mandate for the development of a "deliberate workforce development strategy that increases attainment of key experiences that contribute to a highly qualified acquisition workforce" (10 U.S.C. § 1722[b][2]). And 6 years later, as Acting Under Secretary of Defense for Personnel and Readiness, I signed Department of Defense Instruction 1400.25, Volume 250, which provides, among other things, "a competency-based road map for employees to aid in their career planning and development" (Department of Defense 2016, 8).

Unfortunately, none of these past career-planning efforts has achieved the desired objectives. Careers in the civilian acquisition workforce continue to be largely haphazard and unplanned, and the results continue to be unsatisfactory. As the Section 809 panel acknowledged, "Creating a policy that simply publishes career paths and implements a competency model, without recognizing the heavy lifting needed to change culture" is inadequate (Section 809 Panel 2019, 286).

In fact, the panel's recommendations suffer from the same problem as existing policies: they establish expectations for the acquisition workforce, but fail to provide a mechanism by which those expectations can be met. Model career paths show a rotation of individuals through a progression of assignments and training experiences to build needed skills and competencies. Unfortunately, DoD does not currently have a mechanism for such rotation.

The military personnel system provides a mechanism for concerted career planning because military tours of duty have a limited duration—generally 1–3 years. This means that multiple tours can be used to provide successive experiences needed to build skills and competencies. As a result, young officers who choose a career in acquisition can expect to begin a designed sequence of assignments that includes a progression of developmental acquisition positions, training and education, broadening experiences, staff jobs, and command assignments. This system has been criticized for rotations that are not long enough to build real expertise in specialized fields, but at least it provides a mechanism for long-term career planning.

The civilian personnel system, by contrast, is centered on positions of potentially unlimited duration. An individual is hired for a particular position and can expect to remain in that position indefinitely. The next developmental position will become available only when it is vacated by the individual occupying it. This position-based system provides little opportunity for systematic career planning and progressive assignment along the lines common to the military's rotational system. The stability of the civilian personnel system enables long-serving senior civilians to achieve levels of specialized expertise and institutional memory that are difficult to match in the military, but it is not readily susceptible to systematic career planning.

In the civilian system, individual employees must build their own careers by identifying the next job opportunities and seeking to fill them. Training opportunities and broadening assignments may be available, but are not used to build careers in an organized manner. Supervisory assistance and mentorship are not a sufficient basis for building a workforce because the goals of a local supervisor may not be fully aligned with DoD's goals for the acquisition workforce as a whole.

The Section 809 panel identified this problem when it recommended a public-private exchange program to broaden the experience of defense acquisition professionals. The panel found that multiple exchange programs already exist, but the civilian personnel system discourages their use. Employing offices that participate in exchange programs face the risk of losing talented employees with no prospect for replacement. Employees who participate fear that they could lose their current positions without assurance that an equal or better position will be available upon their return. As a result, these potentially beneficial opportunities remain underutilized (Section 809 Panel 2019, 305–310).

In short, the desire to build a highly-trained and capable career acquisition workforce is in conflict with the civilian employment system as it exists today.

Stepping Away from Position-Based Employment

Existing authorities and requirements could be more effective if employment status were separated from position status. A mechanism is missing that would empower future civilian leaders to build their careers through a series of rotational assignments without fear of losing their jobs. The Federal Government typically hires new employees for specific positions and then treats every promotion or transfer as a new hiring action, subject to a fresh competition. Many private sector employers hire the best talent available and then assign them to a series of positions over time. DoD could do the same.

A cautious first step away from position-based employment would not have to apply to all positions. Rather, employees could opt into specific positions designated as career-building slots, agreeing to a series of rotational, term-limited assignments that would not affect employment status. Ideally, the new program would be administered by functional community managers pursuant to existing guidance (Department of Defense 2016, 2).

In the case of new employees, DoD should take the extra step of separating hiring from placement, using a process referred to as “hiring talent pools” (Panel of the National Academy of Public Administration 2018, 20). Instead of hiring new employees exclusively on a position-by-position basis, as is done now, the Department should hire annual cohorts for an acquisition career track, bringing them into a program that incorporates blocks of training and education along with rotational, career-building assignments. DoD should hire the strongest candidates it can find, train them as a team, and offer them the prospect of steady advancement and new responsibilities.

Cohort hiring would streamline and expedite hiring by establishing a single process to evaluate and make decisions on multiple candidates. It should also make it easier for DoD to access needed talent by offering a career of varied and challenging work from the outset. The greatest competitive advantage the Federal Government has in the job market is the promise of significant responsibility for an important mission. This advantage may be lost on recent graduates who are hired for relatively low-challenge, entry-level positions and left to find their own way to advancement.

To make the new system work, DoD would have to designate developmental positions that would be available for rotation at all levels of the organization so that a wide variety of challenging future assignments would be visible to early-career employees. One option might be having initial assignments of 1 or 2 years followed by longer rotations of up to 5 or 7 years. Assignment terms would not have to be absolute: high-performing employees could be afforded the possibility of moving to new assignments on an expedited basis after developing required skills and competencies. Other options are possible that would not replicate the rigidity of the military rotation system.

New Mindset

The key to this change would be a new mindset: instead of managing positions, DoD would be managing people. Succession planning would no longer be solely about hiring a new person for a particular position. Instead, the objective would be to match individuals who are already in the workforce with the assignments they need to turn them into innovative, productive acquisition leaders. Hiring managers might initially resist losing control over the pool of candidates eligible to fill specific positions, but would ultimately benefit from a streamlined process and better qualified, more productive employees.

The result would be a rotational system for civilian employees that enables career-building opportunities, career-broadening experiences, a constructive mix of training and practical experience, and even public-private exchanges. If DoD gets the rotational system right, the modern acquisition workforce talked about for decades could become a reality.

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Concept for Joint Warfighting[1]

Thomas C. Greenwood and Patrick J. Savage

The U.S. military has mostly been involved in counter-insurgency campaigns in Iraq and Afghanistan since 9/11. The Nation's military is now in the position of having to re-learn how it might fight a large, conventional conflict against nuclear-armed powers like China and Russia. U.S. battlefield victories are far from guaranteed, and the officers responsible for drafting major war plans are new to the challenge, having spent the bulk of their careers facing technologically inferior adversaries like the Taliban. The need for top-down guidance in the form of a joint warfighting concept has never been greater. Without it, the United States stands to lose the next war it fights, and lose badly.

Introduction

Traditional military concepts about joint warfighting are increasingly outdated. For example, the U.S. Army's 1980s era AirLand Battle

Only through development, articulation, and demonstration of a truly joint concept will the Joint Staff, combatant commanders, and military departments be able to shape the capabilities required to deal with the priority threats of China and Russia.

[1] Based on T. Greenwood and P. Savage, "In Search of a 21st Century Joint Warfighting Concept," *War on the Rocks*, September 19, 2019, https://warontherocks.com/2019/09/in-search-of-a-21st-century-joint-warfighting-concept/.

Doctrine—which guided military operations in Desert Storm—does not account for the heightened role of cyber operations, space operations, and information operations in modern warfare. A 2017 update to the joint Air-Sea Battle Concept developed in the 1970s and 1980s underestimated the potential contribution of land forces. While U.S. military departments have been working hard on multidomain concepts since at least 2015, a comprehensive approach is necessary to implement the 2018 National Defense Strategy.[2]

Warfighting Concepts versus Doctrine

More than 40 years ago, Army General Donn Starry defined doctrine as "what is written, approved by an appropriate authority and published concerning the conduct of military affairs." He went on to say, "Doctrine generally describes *how* the Army fights tactically; *how* tactics and weapons systems are integrated; *how* command and control and combat service support are provided; *how* forces are mobilized, trained, deployed and employed" (Starry 1979, 88). Military concepts are thus descriptions of capabilities that do not yet exist but have the potential to solve a military problem.

In Starry's day, the overriding problem was how NATO forces could defend against a Soviet land attack across Europe. Today, joint or multidomain operations must cross air, land, sea, cyber, and space domains and the electromagnetic spectrum to credibly deter China and Russia. Historically, most joint concepts have been developed top-down in a process overseen by the Joint Staff. This process continues as outlined in various modern warfighting documents; however, more work is needed.

Current Efforts to Draft a Joint Concept

The military departments are continuing to develop their warfighting concepts in imaginative ways, though each calls its emerging concept something different:

- Air Force—multi-domain command and control
- Marine Corps—expeditionary advanced based operations
- Navy—distributed maritime operations
- Army—multi-domain operations

Each of these concepts focuses on a different aspect of the problem, and each has adopted different assumptions about war against a major power, which makes them difficult to integrate. Also, while the concepts may comply with Defense Department guidance, they are hardly joint, and they leave little room for combatant commanders to make decisions. Only through development, articulation, and demonstration

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[2] See *Summary of the 2018 National Defense Strategy of the United States: Sharpening the American Military's Competitive Edge*, https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf.

of a truly joint concept will the Joint Staff, combatant commanders, and military departments be able to shape the necessary capabilities. Without that, war with China or Russia becomes more likely *and* more dangerous.

Today's Bottom-Up Approach

Joint concept development relies too heavily on a bottom-up approach that begins independently within each department—a process that pays insufficient attention to integrating efforts into a holistic warfighting concept at the joint level. Accordingly, the bottom-up effort should be complemented by a more robust top-down approach that proactively integrates the bottom-up concepts with the Joint Staff's broader perspective and the combatant commanders' regional- and threat-specific insights. In this way, the best ideas will come together in an adaptive, unified, joint warfighting concept that resonates with U.S. allies and partners.

In one respect, the bottom-up approach is positive because it has stimulated thoughtful discussion at various command echelons and has focused overdue attention on how the military departments can best combine, project, and leverage combat power across all domains. Such a holistic approach is necessary to create multiple dilemmas for an adversary in different domains that span the tactical to strategic levels.

Preparing for Big War

The military departments face two major obstacles in trying to independently develop approaches for great power competition and conflict. First, the current set of concepts have not matured much beyond the working hypothesis level. Second, the concepts require additional rigorous examination and experimentation to assess their feasibility.[3]

For example, the U.S. Army created an experimental Multi-Domain Task Force at Joint Base Lewis in McChord, Washington. Although not yet fully manned, the task force has become the Army's lead tactical organization for testing ways to generate or exploit kinetic and non-kinetic effects across the air, land, sea, space, cyber and electronic warfare domains. Insights gleaned from real-world experimentation may reveal innovative methods for deploying the task force or other Army elements in support of the joint campaign (Judson 2018).

We must not let the Multi-Domain Task Force be a one-off. The historical record indicates that experimentation can point the way to the future, serving as a vehicle for exploring further doctrinal and conceptual possibilities.[4] Given the complex interplay between domains and the still-immature theater implications of cyber and

[3] See K. M. Woods and T. C. Greenwood, 2018, "Multidomain Battle, Time for a Campaign of Joint Experimentation," Joint Force Quarterly (1st Quarter): 14–21, https://ndupress.ndu.edu/Portals/68/Documents/jfq/jfq-88/jfq-88_14-21_Woods-Greenwood.pdf?ver=2018-01-09-102341-740.

[4] See W. Murray, 2002, *Experimental Units: The Historical Record*, IDA Paper P-3684, https://apps.dtic.mil/dtic/tr/fulltext/u2/a412051.pdf.

space capabilities, it is perhaps time to consider forming joint experimentation units or augmenting service-conducted experiments with joint capabilities.

Once the military departments agree on how to conduct all-domain operations, they must ensure that the cohesive, lethal, and time-sensitive application of joint combat power addresses real-world warfighting needs. As lessons learned from Operation Urgent Fury in Grenada revealed, integration does not naturally result from development of the concept process (Stewart 2008, 29+). In a more recent example, U.S. troops and NATO allies still lack secure field interoperability (Sisk 2019, 1), despite numerous directives and technical standards for achieving it.

Full Integration Leads to Convergence

Fully integrating the joint force is necessary to achieve convergence—the U.S. Army term for creating simultaneous effects from all domains faster than the enemy. Convergence happens at the operational level. It requires joint force commanders to orchestrate actions across all domains to create opportunities to advance tailored campaign objectives. This is more than arbitrating between semi-independent, separate warfighting activities occurring in service-specific battlespace that has not yet been integrated with other joint forces or effects.

One approach the joint force commanders can take to facilitate integration and foster convergence is to decide in times of peace how they will organize their forces for war. They have various options available, including designating a subordinate land component commander to control both Army and Marine forces, designating a subordinate maritime component commander to command both Navy and Marine units, or standing up a separate joint task force headquarters. By determining the command-and-control arrangements before war occurs, the joint force will have a baseline of proficiency to train for in peacetime.

"Fight Before the Fight" and Readiness

The gap between what a force can do now and what it might need to do in the future cannot be filled by a single concept that is optimized for all operational challenges. Instead, the military departments should maintain high warfighting proficiency within their respective domains without the expectation that the joint force can successfully conduct all-domain, large-scale, conventional operations around the globe. This can only be realized through an aggressive exercise program at the level of the combatant commands that requires joint force headquarters and component headquarters to collectively engage forces provided by the individual departments in realistic and recurring multidomain-focused training exercises at scale.

The tension between readiness priorities of the various military components is a perennial challenge. Moreover, combatant command headquarters seem unable to routinely provide response cells to support component-level exercises. This missed training opportunity ends up requiring subordinate units to role-play as a higher headquarters for which few are manned, trained, or equipped. During exercises, the joint force needs to repeatedly evaluate its own written concept or an integrated version of military department concepts being practiced. Repetition will not only help assigned units become more proficient at accomplishing their joint missions, it will give the geographic combatant commanders mission-essential feedback necessary to further refine their joint warfighting concepts.

Next Steps

To fill the voids discussed in this article and optimize the development of joint concepts that meet the demands of the 2018 National Defense Strategy, consider the following three initiatives:

1. *Expand the current concept development approaches of the military departments* and invite formations with other departments and combatant command observers to participate in their exercises and experiments. The meaningful insights accumulated over time from these activities will enable geographic combatant commanders to better understand how their assigned forces can be effectively integrated into the joint force and employed in their theaters.

2. *Accelerate the pace and frequency of geographic combatant commanders' joint force experimentation* for conducting multidomain operations against China and Russia. This should start with rigorous examination of how the command will execute critical joint warfighting functions beginning with command and control

3. *Dispatch observer teams from the Joint Staff to exercises and experiments hosted by combatant commands* to gather insights and lessons learned. This practice will not only add context to ongoing Joint Staff efforts to supervise "global integration," but also provide field commanders increased confidence that delegation of authority to the lowest practical echelon is a routine peacetime practice at the four-star level.

Collectively, these initiatives will help reduce institutional friction among the military departments, joint force commanders, and the Joint Staff. More importantly, they will ensure the military departments receive top-down guidance so they can adapt their warfighting approaches to best meet the needs of the joint force commander in the event of war with China or Russia. Assigned forces must understand a joint force commander's vision, campaign sequencing, organization for combat, and general scheme of maneuver before conflict occurs if they are to meet a combatant commander's expectations and standards.

The Stakes

Drafting a warfighting concept that communicates all these vital ideas across the joint force is challenging—but it won't be an academic exercise because the result will go a long way toward deterring China and Russia. If deterrence fails and war ensues, the concept will give the U.S. military an important advantage at a time it needs it most.

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This marks the first time that either Tom or Pat has been recognized for a publication nominated for the Welch Award.

Technology and Military Rotorcraft Mishaps[1]

Christopher A. Martin, Thomas L. Allen, Mark A. Couch,
Paul R. Jones, Jack N. Law, and Joshua A. Schwartz

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

[1] Based on C. Martin, T. Allen, M. Couch, P. Jones, J. Law, and J. Schwartz, "Methodologies to Assess the Influence and Cost Benefit of Technology on Vertical Lift Aircraft Mishaps and Fatalities," *Proceedings of the 75th Annual Forum and Technology Display, Vertical Flight Society*, 2019, https://vtol.org/store/product/methodologies-to-assess-the-influence-and-cost-benefit-of-technology-on-vertical-lift-aircraft-mishaps-and-fatalities-14557.cfm.

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.

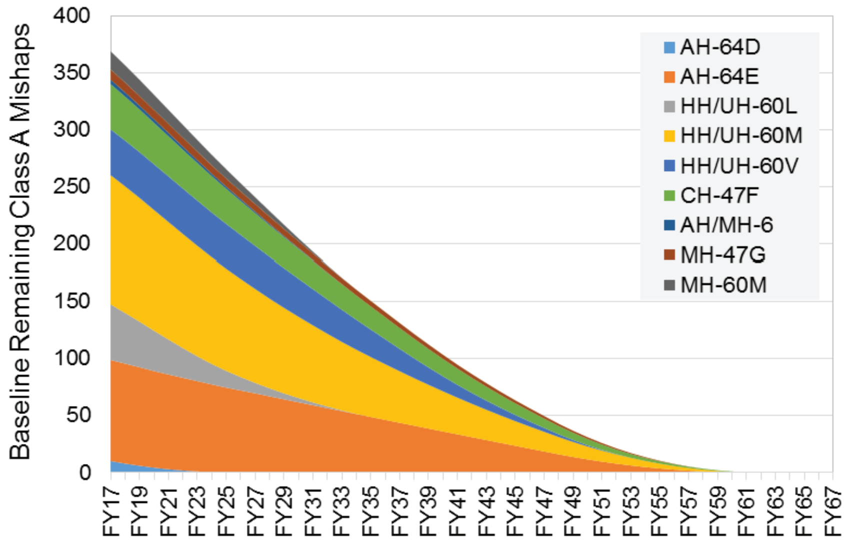

Figure 1. Projected Class A Mishaps Remaining Over Time for U.S. Army Rotorcraft

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.

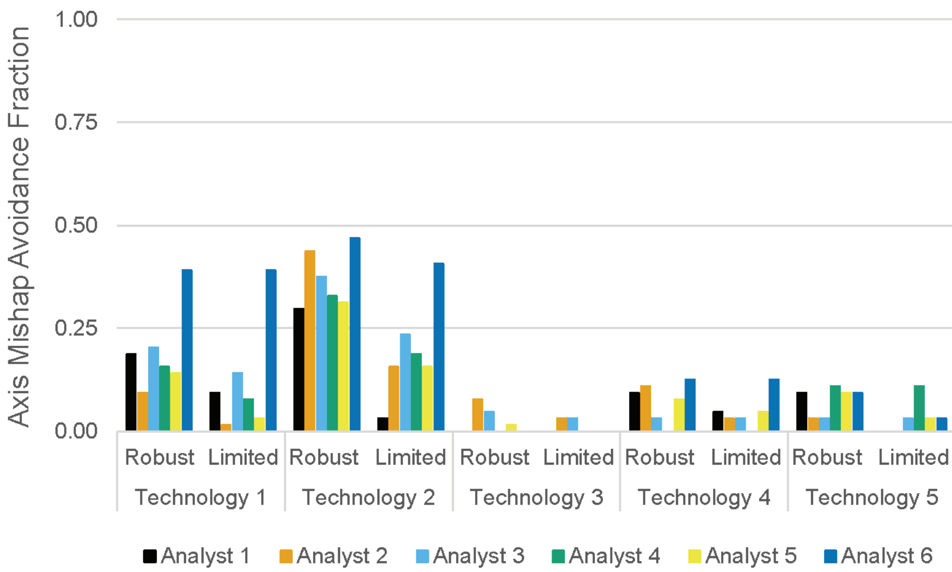

Figure 2. Example Distribution of MAF Scoring for a Single Rotorcraft Type

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).

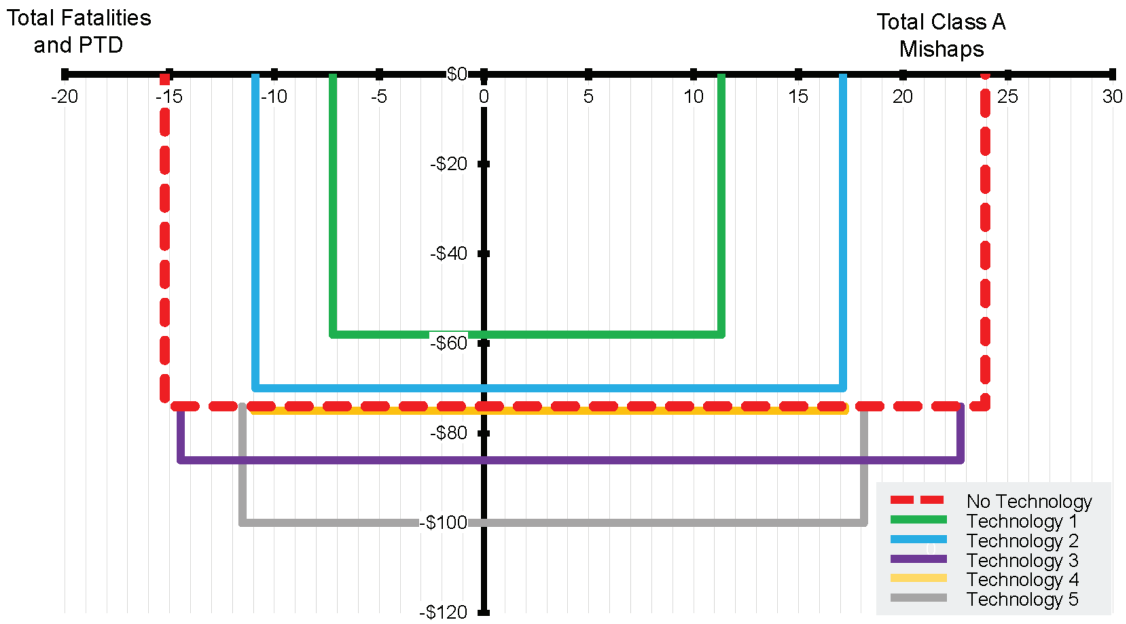

Figure 3. Impact of Technologies on Costs, Lives Lost, and Rotorcraft Lost

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.

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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.

Thomas Allen, an adjunct researcher in the Joint Advanced Warfighting Division, received a PhD in economics and operations research from the Massachusetts Institute of Technology. This is Tom's first time been recognized for contributing to a Welch Award–nominated publication.

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Paul Jones, a member of the research staff in the System Evaluation Division, earned his PhD in mechanical engineering from Northwestern University. This is the first time Paul has been recognized for his participation in the Welch Award competition.

How to Optimize Air-to-Ground Weapon Purchases[1]

Matthew S. Goldberg and David M. Goldberg

The military service branches use modeling and simulation to determine their requirements for nonnuclear weapons fired from aircraft at targets on the ground. The annual modeling exercise is complicated, and solutions take a long time to compute. In this article, a father-son team demonstrate ways to reduce computation time that still offer high-quality solutions to the complex problem of determining requirements for conventional air-to-ground weapons.

Introduction

Determining requirements for U.S. military aircraft weapons involves numerous combinations of delivery aircraft, weapon types, and targets, which makes the modeling problem high-dimensional and slow to converge to a solution.

Two distinct problems need to be solved (see Figure 1). The first problem, *aircraft weapon budgeting*, is at the strategic level. The objective is to

We developed two greedy heuristics that enable us to accelerate the solution to the aircraft weapon budgeting problem, with minimal loss in the quality of the solution.

[1] Based on M. S. Goldberg and D. M. Goldberg, "Optimizing the Purchases of Military Air-to-Ground Weapons," *Military Operations Research* 24, no. 4 (2019): 37–52, https://www.jstor.org/stable/26853512.

determine the optimal inventory of air-to-ground weapons for fighting in a particular wartime scenario; the next several years' budgets are devoted to procuring that inventory. The second problem is *weapon target assignment*, which occurs at the tactical level in the theater of military operations. As part of their daily air tasking orders, air operations commanders match weapons in their local inventories with potential targets to destroy the highest-value set of targets (see U.S. Department of Defense, Joint Chiefs of Staff 2019). The ability to hit targets is constrained by the number of sorties (missions) available in the wartime theater for each aircraft that can feasibly deliver each type of weapon.

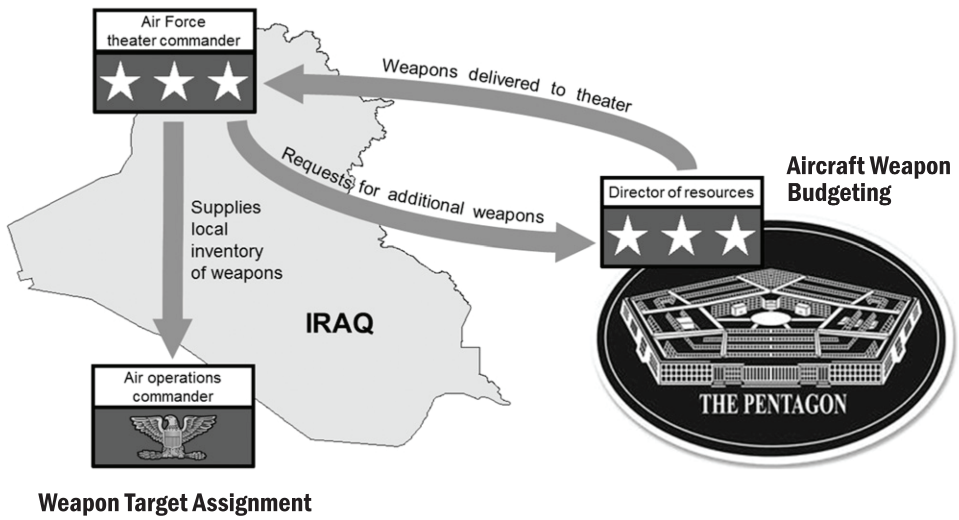

Figure 1. Relationship Between Aircraft Weapon Budgeting and Weapon Target Assignment

The military branches generally use nonlinear programming to solve these problems, and that is our approach as well. In our original paper, we made three major contributions:

1. We extended the work of Boger and Washburn (1985) by deriving an expression for the expected number of targets that would be destroyed when multiple aircraft-weapon combinations attack a given target population, and when some "dead" targets appear "live" and act as decoys.

2. We demonstrated the applicability of two heuristics that identify the preferred weapons to maximize a utility function defined over various types of targets destroyed.

3. We investigated the ability of those two heuristics to reduce the dimensionality of the problem and accelerate the solution.

This article summarizes the last two of these contributions. We developed two greedy heuristics that enable us to accelerate the solution to the aircraft weapon budgeting problem, with minimal loss in the quality of the solution.

Current Practice

The military branches often estimate their requirements for aircraft weapons in two stages. They do not impose an explicit budget constraint in the optimization model during the first stage, but only constraints based on the number of sorties available in the wartime theater. The solution to that problem generates requirements for weapons, to which they apply cost factors to estimate the budget needed to fully purchase them. The budget amount is treated as an output (byproduct) of the optimization rather than an input (constraint). Next, they run budgetary excursions in which they incrementally reduce the budget below 100 percent to see how the optimal solution changes and how much wartime capability is sacrificed. The budgetary excursions also highlight cases in which the optimal inventory is too expensive to purchase in the next year's budget (netting out current inventories), and has to be spread out over several years' budgets in the future.

Greedy Heuristics

We wondered whether greedy heuristics would be useful in either partially characterizing or fully computing a solution. A simplified version of our problem is similar to the fractional (or continuous) knapsack problem first studied in a classic paper by Dantzig (1957), who developed a "bang-per-buck" criterion for entering variables into the solution.

As a first step, we reduced the number of aircraft-weapon-target combinations considered in aircraft weapon budgeting by omitting those we deemed infeasible. The infeasible combinations included aircraft that cannot carry certain types of weapons and aircraft-weapon combinations that are not effective against certain targets. We next developed two heuristics that further reduce the number of aircraft-weapon-target combinations to be considered.

Either heuristic, or a hybrid of the two, greatly reduces time to produce a solution for the particular circumstances. We identified two cases in which the smaller, faster-running model produced the same number of expected kills as the full model: (1) the number of sorties available to deliver the weapons in the scenario being modeled is unlimited or (2) the weapon procurement budget is unlimited. These cases—called "edge cases"—although unlikely, demonstrate the gain in computational speed by pre-screening the aircraft-weapon-target combinations to a reduced number. Our research question was whether the improvement in computational speed outside of the edge cases comes at the price of some degradation in the quality in the solution—the utility provided by the expected numbers of targets destroyed of each type. Details about these heuristics follow.

Least Cost to Kill

Goldberg (1991) supplied mathematical conditions under which the least cost-to-kill (LCTK) criterion identified the optimum combination for destroying a single type of target when the budget constraint is binding but the sortie constraints are not. The cost-to-kill ratio divides the cost to purchase a weapon by its pure probability of kill against the target type, without adjustment for decoys. That ratio is minimized or, equivalently, its inverse ratio—"bang-per-buck"—is maximized. The LCTK heuristic eliminates choice variables from the optimization problem that would never appear in positive quantities in the optimal solution under the specified circumstances. However, the LCTK heuristic only partially characterizes the solution to the nonlinear program. The heuristic determines the aircraft-weapon combination to use against a particular target type but not the allocation of budget dollars to destroying each type.

Expected Kills per Sortie

We complemented Goldberg's previous research by exploring a greedy heuristic in the converse situation, when the sortie constraints are binding but the budget constraint is not. The expected kills-per-sortie (EKS) heuristic considers only combinations that destroy the most targets per sortie. This criterion, like the LCTK criterion, favors weapons with a high probability of kill; but rather than contrasting that probability against procurement cost, it favors aircraft with a high load factor so that more weapons can be delivered on a single sortie.

In an illustrative analysis of the EKS heuristic, we considered an aircraft that can carry either four 500-pound bombs or two 1,000-pound bombs on a single sortie. A sortie against unprotected or immobile targets might destroy an average of 1.2 targets if loaded with four 500-pound bombs but only 1.0 targets if loaded with two 1,000-pound bombs. However, a sortie against heavily defended or moving targets might destroy an average of 1.6 targets if loaded with four 500-pound bombs but 1.8 targets if loaded with two 1,000-pound bombs. The EKS heuristic would steer the model solution toward the preferred weapon type in both situations.

Performance Exercise

Next, we performed a computational exercise to demonstrate the tradeoff between increased calculation speed versus loss of quality when using these heuristics. We estimated the computational advantage to prescreening the aircraft-weapon-target combinations so that only those satisfying either the LCTK criterion or the EKS criterion enter the problem. Using a realistically sized problem for the U.S. Air Force, we compared results using our heuristics against results obtained with the full optimization model after one hour of calculation time. In our simulations, the heuristics often came up with a solution in just 10 minutes that was superior to the solution the full model came up with in an hour.

Approach

We drew our parameters primarily from Wirths (1989), who provided an unclassified data set derived from the U.S. Air Force's then-current Joint Munitions Effectiveness Manual. Wirths supposed that two aircraft were available to fly sorties limited to 108 and 81, respectively, over the course of a campaign. He considered 24 weapon types and 13 target types. For the target types, he provided target populations, their relative utility values, and decoy rates.

Wirths did not provide data pertaining to weapon costs, load factors, or kill probabilities, so we simulated these parameters to allow us to test the efficacy of our heuristics under a variety of conditions. In all, we generated 10 sets of random parameters to use in our experiments. For each set of parameters, we tested a series of four models: the full aircraft weapon budgeting model (no heuristic), the EKS model, the LCTK model, and a hybrid model having all of the variables in the EKS and LCTK models. All models were run using IBM ILOG CPLEX optimization modeling software on an Intel Core Duo central processing unit at 2.67 gigahertz.

We allowed the full model a maximum runtime of one hour, and each heuristic model was permitted a maximum runtime of 10 minutes. We first ran each model with no budget constraint and recorded the highest budget requested by any of the models. We then tested each model with a budget constrained to, respectively, 90, 80, 70, and 60 percent of the unconstrained requirement.

Results

We provide the results of our demonstration in Table 1, where the highest performing figures at each budget level is in bold. The results show that the speed-quality tradeoff is quite favorable: by applying the heuristics, solutions were calculated much faster and the quality was only occasionally less than that of full models to which we did not make any predetermined exclusions of aircraft-weapon-target combinations. Having the choice of three heuristics allows for useful alternatives to the full budgeting model across the entire range of budget constraints tested.

Table 1. Comparison of Results for 10 Sets of Parameters

	Budget constraint	Full model	EKS model	LCTK model	Hybrid model
Panel A: Average objective values	100%	838.1	**853.7**	736.5	850.1
	90%	723.4	701.5	697.8	**728.4**
	80%	647.3	594.6	**654.2**	648.8
	70%	599.7	537.2	**610.0**	602.6
	60%	489.0	456.5	**506.1**	493.5
Panel B: Average weighted kill percentages	100%	73.4%	**75.1%**	64.8%	75.0%
	90%	63.7%	61.8%	61.6%	**64.1%**
	80%	57.5%	52.7%	**58.5%**	57.8%
	70%	52.7%	47.7%	**53.9%**	53.6%
	60%	43.3%	40.5%	**45.0%**	44.0%
Panel C: Counts of objective values superior to full model	100%	n/a	**10**	0	9
	90%	n/a	2	3	**10**
	80%	n/a	0	**8**	**8**
	70%	n/a	0	**10**	8
	60%	n/a	0	**10**	**10**

When assigning an unlimited budget, we found that the EKS model yielded superior objective values relative to the full model in all 10 trials despite being given a maximum of only one sixth of the solve time. EKS model solutions required an average of only 13.8 seconds to eclipse the objective value that the full model achieved in an hour. Thus, even when run for only a short period of time, the EKS model provided excellent results for estimating military requirements. The EKS model was not nearly as effective when run with restrictions upon the budget. When the budget was restricted to 90 percent, the EKS model achieved superior solutions only twice in 10 trials, and when the budget was even further restricted, the EKS model did not produce any superior solutions (Panel C of Table 1).

Compared to the EKS model, the LCTK model performed particularly well with a budget constraint below 80 percent, providing superior objective values relative to the full model in all 10 trials with budgets of 60 and 70 percent. At a budget of 60 percent, the LCTK model required an average of 31.1 seconds to eclipse the full model's objective values, and at a budget of 70 percent, it required an average of 74.7 seconds. The LCTK model was fairly versatile in that it was effective at various budget levels.

The hybrid model was effective regardless of the level of budget. On average, it produced superior solutions relative to the full model across all budget constraints that we tested, and it outperformed the full model in 45 of 50 pairwise comparisons.

In short, when examining military requirements with an unlimited budget, the EKS model provided an expedient alternative to the full model. Conversely, when considering a situation in which the budget is quite restricted, the LCTK model reliably supplied superior solutions in short periods of time. The hybrid model provided excellent solutions regardless of the budget constraint, and it is especially useful when applied in situations with a moderate budget constraint.

The results observed are explained, in large part, by the extent to which each heuristic reduces the size of the problem being solved. In mathematical terms, we use X_{ijk} to denote the number of weapons of type *j* delivered by aircraft of type *i* against targets of type *k*. The full models that we generated using the 10 samples studied averaged X_{ijk} variables numbering 152.4.

As shown in Table 2, the number of variables considered by our heuristic models varied widely, while the number of positive (nonzero) X_{ijk} variables in the solutions they reached show far less variability. The full model expended great computational effort with variable selection, whereas the heuristic models determined many or most of the positive variables in advance.

Table 2. Variables Considered

	Average number of Xijk variables	Average number of positive Xijk variables	Average percentage of Xijk variables selected
Full model	152.4	19.7	12.9%
EKS model	26.0	13.6	52.4%
LCTK model	13.0	9.1	70.0%
Hybrid model	38.8	17.1	44.1%

Conclusion

We used analytical and numerical methods to complete the theoretical understanding of the military's aircraft weapon budgeting problem. First, we extended the work of Boger and Washburn (1985) by deriving an expression that accounts for the possibility that some dead targets may appear live, acting as decoys and drawing additional fire.

Second, we demonstrated the applicability of two greedy heuristics that identify the preferred weapons to maximize a utility function defined over targets destroyed of various types. Goldberg (1991) had provided a formal justification for the LCTK heuristic, in a situation where a binding budget constraint exists but sortie constraints do not. We developed a corresponding criterion using highest EKS for the converse situation in which binding sortie constraints exist, but the budget constraint does not. Although a monetary cost-to-kill ratio does not apply in such a situation because there is no active budget constraint, the scarcity of sorties motivates an alternative criterion. In this latter situation, the preferred weapons are those that economize on scarce sorties by offering the highest EKS.

Finally, we investigated the ability of those two heuristics to reduce the dimensionality and accelerate the solution in a realistically sized problem for the U.S. Air Force. The EKS heuristic correctly preselects the aircraft-weapon combinations that appear in the optimal solution when the procurement budget is fully funded. For our Air Force example, when the procurement budget is set at 60 percent to 80 percent of full funding, the LCTK heuristic achieves a better solution than the full optimization model does in a fraction of the runtime. When the procurement budget is set at about 90 percent of the requirement, the solution may be accelerated by a hybrid approach that includes only the subset of aircraft-weapon combinations that are suggested by either of the two heuristics.

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Reconciling U.S. Democracy Promotion and Military Assistance to African Forces[1]

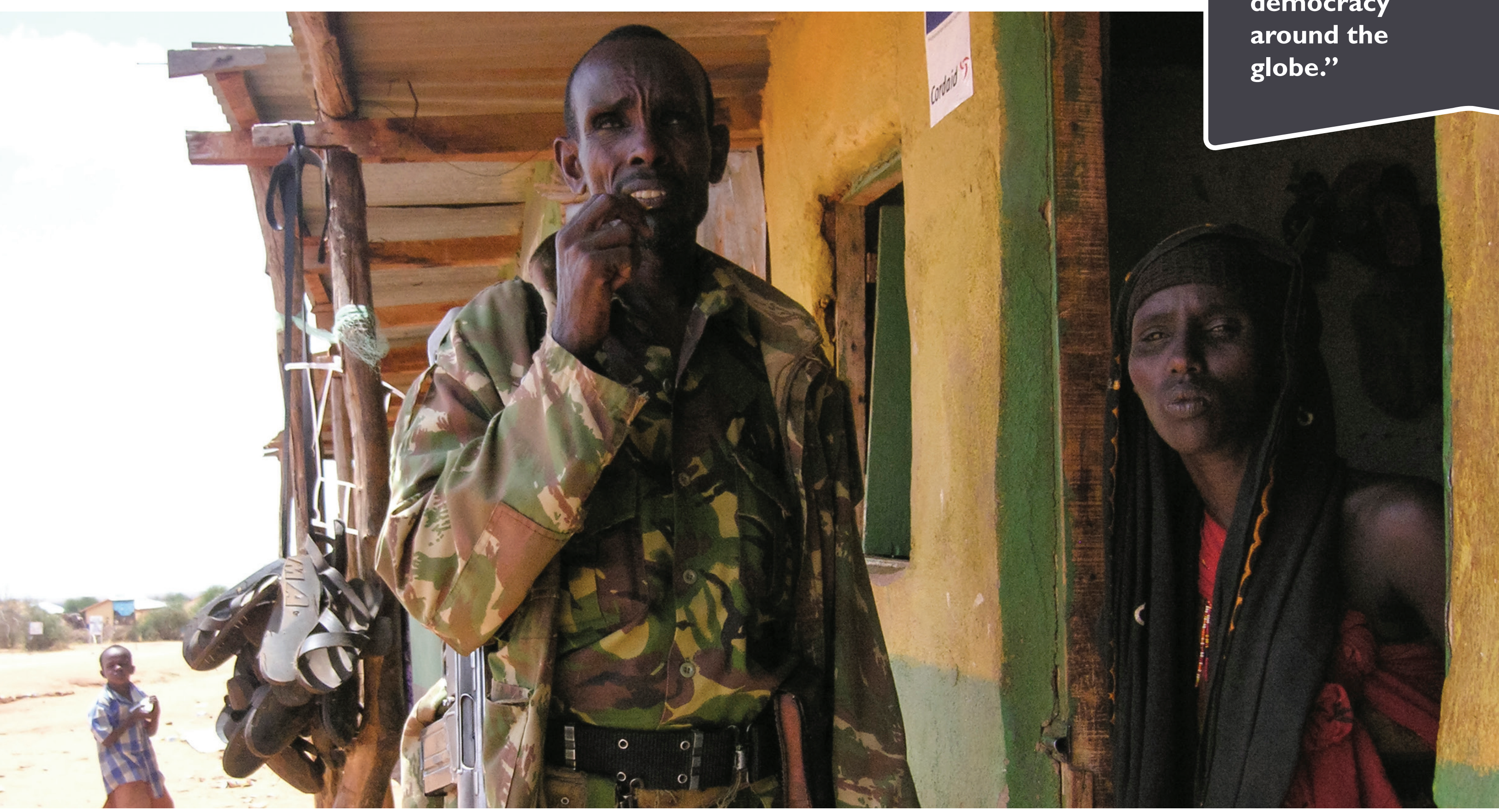
Stephanie M. Burchard and Stephen Burgess

The U.S. has developed long-term military partnerships with several African countries that have less than stellar human rights records. Yet, the U.S. chooses to rebuke some of these countries for human rights abuses, while continuing partnerships with others accused of similar abuses. An in-depth analysis of U.S. security partnerships with Burundi, Ethiopia, Kenya, Nigeria, Rwanda, and Uganda from the 1990s to 2017 found several reasons for this seeming inconsistency.

"By satisfying short-term goals through a more transactional approach to human rights and security partnerships, the U.S. risks damaging its longer term goals of nurturing democracy around the globe."

Introduction

Respect for human rights has been one of the foundational tenets of U.S. democracy promotion for decades. In the early 1960s, Congress required the U.S. State Department to issue an annual *Human Rights* Report on every country in the world. In the late 1990s, the Leahy Law was introduced, prohibiting the United States from providing assistance to military units accused of gross human rights abuses. As recently as 2017, the National Defense Authorization Act required human rights



[1] Based on S. Burchard and S. Burgess, "U.S. Training of African Forces and Military Assistance, 1997–2017: Security versus Human Rights in Principal-Agent Relations," *African Security*, 2018, https://doi.org/10.1080/19392206.2018.1560969.

training for every security assistance program. The reality of U.S. foreign assistance, however, is less straightforward than these and other laws would make it seem, particularly when U.S. security needs come in direct conflict with commitments to democratic norms.

We used qualitative data from Burundi, Ethiopia, Kenya, Nigeria, Rwanda, and Uganda to answer questions surrounding this conflict. Specifically, we wanted to understand the conditions under which the U.S chooses to censure offending countries and when it does not. Given that the African continent as a whole is often perceived to be of lesser importance to U.S. policymakers than other continents (van de Walle 2015), policymakers should be able to assert human-rights-based decisions more readily than in regions deemed more important.

U.S. Policy on Military Assistance in Africa

In line with the African Union's goal of providing African solutions to African problems, U.S. security policy in Africa has focused on training and equipping forces that are available for deployment and that are willing to operate in less than permissive environments in the interests of the United States. The U.S. would rather have African forces deal with the continent's crises and conflicts than put American military personnel in harm's way. As such, U.S. training and joint exercises have attempted to improve military professionalism and increase capabilities and operational capacity.

The U.S. relationship with African regimes and military forces it chooses to engage with is captured in *principal-agent theory*. In this theory, the U.S. is the principal, offering training and equipment to further its own security interests, and African regimes and forces are agents addressing the security challenges of interest to the U.S. The inherently asymmetric distribution of information in the principal-agent relationship allows the agent to take actions not in the principal's interest (Weingast 1983). One of two approaches can be taken to remedy the situation, as the next subsection describes.

Rationalist versus Constructivist Approaches

The *rationalist* approach holds that the principal is a single rational entity that contracts a rational agent to carry out a task likely to meet the principal's interests in a timely manner with the least possible cost and the greatest possible returns (Shepsle 2006). The principal has various positive and negative incentives at its disposal to persuade the agent to carry out the terms of the contract to the principal's satisfaction (Miller 2005. Agents that carry out contracts to the principal's satisfaction earn trust and contract renewal; those that do not can be sanctioned or dropped from the principal's consideration (Cooley and Ron 2004, 487).

The *constructivist* approach emphasizes the social process the principal uses to understand and contract with the agent (Dees 1992, 28). With this approach, the principal can specify appropriate countermeasures—or reject inappropriate countermeasures—to change an agent's problematic behavior (Rittinger 2017, 398).

Some U.S. government policymakers believe agent behavior is modifiable through further training (rationalist) while others insist that agent conduct can be changed only by withholding training and equipment valued by the agent (constructivist). We believe that the constructivist approach provides a more complete explanation for the disparate U.S. application of negative incentives, such as sanctions, to African agents that commit human rights violations.

Modernization versus Accountability Schools

Two competing schools of thought also affect how the U.S. applies sanctions to its security partners. In the *modernization school* of thought, which emerged in the 1940s, the U.S. trains and educates underdeveloped nationalist proxies to produce modern militaries able to carry out the principal-agent contract at lower cost than previously experienced. In the 1970s, the accountability school offered that militaries could still abuse human rights even after being trained and educated and only sanctions would lower costs (Ladwig 2017, 5–6).

Principal-Agent Theory in Africa

Application of the constructivist principal-agent theory in Africa places the modernization and accountability schools at odds about how much and for how long agents that shirk their human rights responsibilities should be sanctioned. The outcomes of these struggles are demonstrably the source of variations in the level and longevity of U.S. sanctions against norm-violating agents. Further, the dominance of one school over another changes over time. Our research indicates that the U.S. has been leaning toward modernization over accountability given the rise of violent extremist organizations in Africa since the mid-2000s.

With the goal of explaining the outcome of U.S. policy disputes internal to the government, we ask the following research question: When do human rights interests prevail over U.S. interests in providing security assistance?

Case Selection and Analytical Approach

To answer this research question, we used a qualitative case study design and selected the cases of Burundi, Ethiopia, Kenya, Nigeria, Rwanda, and Uganda. U.S. security cooperation has been the greatest in those countries and yet norm violations, such as human rights abuses, have frequently been committed. Comparing these cases to one another and noting changes in U.S. policy in each country over time while holding country-specific features constant, such as population size, ethnic fragmentation, and regime type, allowed us to see the nature and severity of norm violations and U.S. reactions to them.

A clear picture of changes in troop availability over time emerged by examining these cases in chronological order from 1997 to 2017. For example, from 2006 onward, Nigeria and Rwanda increased their troop contributions to three battalions in Darfur and had more units maintaining homeland security and deploying to other missions. That commitment in Darfur made it difficult for the two countries to deploy troops to Somalia in 2007. The inference is that timing and availability were significant variables in a country's willingness to commit troops.

The amount of training and annual security assistance the U.S. provided were also important in analyzing cases. For example, the U.S. had greater sunk costs in Burundi than in Kenya, having trained 35,000 Burundians versus only 850 Kenyans. However, the U.S. provided Kenya with tens of millions of dollars in annual security assistance for years, which also represents sunk costs. Therefore, U.S. training needs to be contextualized by the overall strength of the relationship and the size of the resource investment.

We used the annual amount of U.S. foreign assistance per person allocated to each country as a proxy measure for U.S. government interest in that country. Overall foreign assistance includes both economic assistance and military assistance, which better captures the entirety of U.S. interests than military assistance alone would. We based relative military importance of each country on the number of times that country was mentioned in U.S. military commanders' annual posture statements to Congress from 2001, the first year for which data were available, through 2017. Taken together, these two indicators—foreign assistance and military importance—provide us with a good picture of the overall emphasis the U.S. places on its relationship with a partner nation.

Results

In some years, the U.S. was willing to overlook norm violations and in other years it was not. The decision to overlook violations crossed multiple U.S. presidential administrations, suggesting it was not purely the prerogative of the political actors in power that determined the nature of the response. Most instances of norm violations by countries in which the U.S. had a high interest earned either no response or a limited one. Conversely, the U.S. imposed severe sanctions by either mostly or completely suspending assistance in every case where interests were low and violations were high. Summaries by country follow.

Burundi

The United States did not punish Burundi following reports of sexual abuse in Somalia by Burundi National Defense Force troops in 2014. However, Burundi soldiers engaged in U.S. training and exercises were vetted via the 1997 Leahy Law's process to ensure they were not involved with the military units accused. After repressive norm violations by the Nkurunziza regime and Burundi National Defense Force in 2015 and 2016, U.S. peacekeeper training was suspended, though counterterrorism training was maintained. Burundi was a high-interest country for the U.S. because of its willingness to participate in the African Union Mission in Somalia, along with Ethiopia, Kenya, and Uganda.

Ethiopia

Ethiopia has been a high-priority country for the U.S. since the mid-2000s because of its strategic location in the Horn of Africa and its willingness to fight in Somalia. A series of moderate human rights violations by the Ethiopian regime against internal opposition received either no response or a limited response from the United States. Members of Congress attempted at a few points to rebuke Ethiopia for its norm violations but never succeeded in pushing any meaningful sanction forward. In the late 1990s, however, Ethiopia was of a lower priority, and its brief war with Eritrea provoked a severe U.S. response—suspension of all security assistance.

Kenya
Kenya has long been a high priority U.S. partner, particularly in counterterrorism efforts, and despite the nature or severity of Kenya's human rights violation, the U.S. has appeared unwilling to adjust its security assistance posture since at least the late 1990s. Kenya security and police forces were accused of human rights abuses involving political repression or extrajudicial killings on several occasions from 2007 through 2017, but none of the allegations resulted in the suspension of U.S. military assistance. In fact, support provided to Kenya increased in the mid-2010s.

Nigeria
U.S. interest in Nigeria has waxed and waned over time. When Nigeria's importance was low, the U.S. was much more likely to impose sanctions and suspend security assistance. When Nigeria increased in importance, the U.S. was much less likely to impose sanctions for norm violations, regardless of severity. Sanctions against Nigeria from 2014 to 2015 were imposed despite high U.S. interests, but the sanctions were brief and assistance soon resumed, even increasing in 2015. This pattern is similar to that seen in Burundi. The U.S. may have been more willing to impose severe sanctions in Nigeria due to the number of partnership alternatives it had in the region at the time.

Rwanda
Rwanda's support to rebels in the Democratic Republic of the Congo provoked the U.S. to suspend security assistance from 2012 to 2014, when U.S. security interests in the country were high. However, this decision came as U.S. interest in Darfur (and consequently Rwanda's support to that mission) was waning. The U.S. did not sanction Rwanda for equally high human rights violations that had occurred in 1996.

Uganda
In Uganda in 1998, the U.S. responded to allegations of human rights abuses by the Ugandan People's Defence Force in the Democratic Republic of the Congo by completely suspending training assistance. Compared to large-scale massacres, these were relatively minor infractions but nonetheless resulted in substantial loss of assistance. During the height of Uganda's importance to the U.S. and because of its assistance in Somalia, the U.S. imposed only limited sanctions against the regime for its ongoing criminalization of homosexuality; repeated accusations of sexual abuse by Ugandan People's Defence Force troops in peacekeeping operations were overlooked.

Summary
Our examinations of the six African cases revealed that the U.S. partially punished Burundi (high U.S. interests with high violations at home and minor ones abroad), severely punished Nigeria (moderate U.S. interests with high violations at home and minor ones abroad), and severely punished Rwanda (declining high U.S. interests with minor to moderate violations abroad). These responses contrast sharply

with the United States' non-punishment of Uganda and Kenya (high U.S. security interests with minor violations abroad and moderate violations at home).

Table 1 shows measures of importance over time for the six African cases alongside descriptions of their norm violations and U.S sanctions in response. The importance of a country to the United States is positively correlated with U.S. foreign assistance to that country in every case except for Nigeria in 2014. (We speculate that the distortion may have to do with Nigeria's population, which exceeded 190 million in 2017.) A country's substantive security interest to the U.S. is based on the relative number of conflicts, if any, the partner country was involved in, and how important resolving these conflicts appeared to be to the United States.

Table 1. Chronology of U.S. Interests and Sanctions for Norm Violations in Six African Countries

Year	Country	Posture Statement Mentions*	U.S. Foreign Assistance per Person per Year	U.S. Security Interest Level (Substantive Reason)	Norm Violation Level (Description)	U.S. Response Level (Form)
1993	Nigeria	N/A	$0.1	Low (Economic Community of West African States Monitoring Group)	High (military human rights abuses)	Severe (military assistance suspended)
1996	Rwanda	N/A	$33.0	High (post-genocide military)	High (invasion of the Democratic Republic of the Congo)	None
1998	Ethiopia	N/A	$2.5	Low	High (war with Eritrea)	Severe (African Crisis Response Initiative suspended; military aid cancelled; weapons sales suspended)
	Uganda	N/A	$5.6	Low	High (invasion of Democratic Republic of the Congo)	Severe (African Crisis Response Initiative suspended)
2003	Nigeria	3	$0.7	Low	High (Benue massacre)	Severe (international military education and training/foreign military financing suspended)
2005	Ethiopia	3	$8.0	High (Somalia)	Moderate (postelection violence)	None
2008	Kenya	6	$14.5	High (counterterrorism)	High (postelection violence)	None
2013	Rwanda	0	$15.0	High (African Union Mission in Somalia)	High (support to M23 militia rebels, who used child soldiers and committed human rights abuses)	Severe (international military education and training/foreign military financing suspended)
2014	Nigeria	10	$3.0	High (Boko Haram)	Moderate (military human rights abuses)	Limited (military assistance reduced)
2015	Burundi	0	$4.5	High (African Union Mission in Somalia)	Moderate (autocratic power grab)	Limited (Africa Contingency Operations Training Assistance suspended; counterterrorism training continued)
	Ethiopia	1	$7.5	High (African Union Mission in Somalia)	Moderate (state repression)	Limited (congressional sanctions adopted; military assistance exempted)
	Uganda	3	$13.4	High (African Union Mission in Somalia; Counter-Lord's Resistance Army)	Low (anti-homosexual legislation)	Limited (regional military exercise cancelled)
2016	Kenya	3	$22.4	High (African Union Mission in Somalia)	Low (extrajudicial killings)	None

N/A—not applicable.
* Posture statements not available before 2001.

Discussion

We found the comparative weight of interests to foreign assistance values (sunk costs) determined U.S. responses to norm violations. A combination of the intensity of U.S. interests and the magnitude of the norm violation explained when the U.S. chose to censure a country as well as the form of the rebuke. Countries where the U.S. had significant interest were often exempted from censure. As seen in Table 1, the U.S. opted to severely respond to norm violations when U.S. interests were high only once, in Rwanda.

This finding indicates that the modernization school of thought has prevailed over the accountability school in the constructivist approach to principal-agent theory. That is, those who believe African militaries who commit human rights violations can be improved through continuous engagement and training wielded more policy-making influence than those who believe that the U.S. should disengage from and sanction those militaries.

The cases we examined demonstrated that timing, availability, interests, and capability were all important in determining the agents in Africa that the U.S. contracted to carry out missions in its security interests. U.S. security interests in Africa tended to outweigh human rights interests when U.S. security interests were high and human rights violations were low. However, when norm violations were high, the U.S. sanctioned the agent at least partially, giving agents a chance to redeem themselves, also in line with the modernization school.

The accountability school prevailed temporarily in Nigeria, Rwanda, and Burundi where human rights abuses were high but not in Ethiopia, Kenya, or Uganda, which played an important role in helping to meet high U.S. interests. In addition, the temporary nature of sanctions in Nigeria, Rwanda, and Burundi reflects both a decline in U.S. human rights interests in Africa policy since the 1990s as well as predominance of modernization advocates over accountability supporters when it comes to U.S. security interests in Africa.

While the U.S. commitment to democracy and human rights in Africa is rhetorically robust, its practical commitment is fluid and subject to influence by its security needs. By satisfying short-term goals through a more transactional approach to human rights and security partnerships, the U.S. risks damaging its longer term goals of nurturing democracy around the globe. It also runs the risk of reputational harm associated with the selective enforcement of democratic norms.

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Predicting Effects of Toxic Inhalation Exposures[1]

Alexander J. Slawik, Nathan Platt, and Jeffry T. Urban

The toxic load model is a popular way to assess inhalation hazards posed by exposure to toxic chemicals. The model is well-defined for constant-concentration exposures, but several generalizations for time-varying exposures have not been validated by experimental evidence. We independently analyzed data from a three-year experiment on rats of time-varying exposures to inhaled toxins to assess the utility of the toxic load model and its proposed extensions to the hazard prediction modeling community.

Introduction

The toxic load model is a phenomenological exposure-response model of the effects of inhalation of toxic industrial chemicals. It was designed to improve upon Haber's Law, which states that toxic effects depend only on dosage, usually measured by the time-integrated airborne chemical vapor concentration. The toxic load model attempts to account for time-dependent biological response indirectly by replacing dosage as the measure of exposure with a quantity called the toxic load.

Our results raise the question of how best to model the toxic effects of acute inhalation exposures for the complex time-varying atmospheric concentration profiles characteristic of real-world airborne toxic release incidents.

[1] Based on A. Slawik, N. Platt, and J. T. Urban, "User-Oriented Independent Analysis of the Toxic Load Model's Ability to Predict the Effects of Time-Varying Toxic Inhalation Exposures," *Regulatory Toxicology and Pharmacology* 106 (August 2019): 27–42, https://doi.org/10.1016/j.yrtph.2019.04.003.

Previous research by ten Berge, Zwart, and Appelman (1986) showed that the toxic load model fits exposure-response data better than Haber's Law for certain chemicals. However, most experimental work to parameterize and validate the model used only steady exposures of constant concentration. This type of exposure is not representative of real-world atmospheric dispersion events, in which atmospheric turbulence can lead to highly fluctuating and intermittent chemical vapor concentrations due to in-plume turbulence and turbulent plume meander, respectively (Wilson 1995).

The Naval Medical Research Unit Dayton (NAMRU-D) conducted a three-year experimental campaign of the effect on rats of time-varying exposures to hydrogen cyanide (HCN) or carbon monoxide (CO) (Sweeney, Sharits, Gargas, et al. 2013; Sweeney, Summerville, and Channel 2014; Sweeney, Summerville, Channel, et al. 2015; Sweeney, Summerville, Goodwin, et al. 2016—collectively referred to hereafter as Sweeney et al.). The U.S. Army's Edgewood Chemical and Biological Center (ECBC) designed and managed the experiments.

We independently analyzed the ECBC/NAMRU-D data to assess the potential utility of the toxic load model and its proposed extensions to the hazard prediction modeling community. None of five proposed extensions to the toxic load model for the case of time-varying exposures in the literature have been validated. None of these proposed extensions have been definitively demonstrated to be preferred over another.

Methodology

Our analysis methodology focused on applying and assessing the toxic load model within a user-oriented context, which differs from that used in the ECBC/NAMRU-D experiments. We tried to emulate the hazard prediction modelers' practice of estimating the number of human casualties. They estimate casualties using time series of atmospheric concentrations. To do so, they apply a chosen extension of the toxic load model to the concentration time-series data. They typically express the toxic load model in terms of parameters using data from the toxicological literature. Our method follows a similar procedure to predict lethality for each trial in the ECBC/NAMRU-D experiments.

We generated predictions for each of five proposed extensions of the toxic load model to the case of time-varying chemical vapor concentrations. We applied statistical measures of scatter and bias to determine the degree of agreement between toxic load model predictions and observations, and performed statistical tests to determine whether any disagreement between predictions and observations is within the range that is expected from small sample size errors (i.e., variability due to small numbers of rats per exposure in the laboratory experiments). Our analysis methodology is not designed to explain differences between model predictions and experimental observations; it merely quantifies those differences so that model users can determine how much confidence they should have in their modeling protocols.

In our analysis protocol, we considered the HCN data and CO data separately, but combined the 2012 and 2013 HCN data sets. For each type of exposure, HCN or CO, we applied a multi-step analysis protocol:

1. Fit the toxic load model using constant-concentration exposure data to determine the toxic load model parameters
2. Determine regimes of exposure duration in which the constant-concentration exposure data are well-fit by the toxic load model
3. Compare model predictions to laboratory observations for all trials for each time-varying exposure profile and each proposed extension to the toxic load model
4. Assess the predictive performance of each proposed extension to the toxic load model
5. Determine regimes of exposure duration in which model predictions using the time-varying exposure data agree with observations

It's important to note that our method differs from the original work in several ways, leading to different conclusions. Our objective was to help the hazard prediction modeling community understand how much confidence they should have in their toxicology models, so our analysis methodology is designed to determine how well the predictions of the toxic load model and its time-varying extensions match experimental observations. We therefore compared the predicted and observed fractions of rats that died in each trial. Sweeney et al. used more indirect measures: they compared derived toxicity parameters to each other on a profile-by-profile basis. In general, Sweeney et al. sought to verify the applicability of the toxic load model to the case of time-varying profiles by demonstrating that the derived toxic load parameters were consistent from profile to profile.

We also employed a user-oriented approach in our data-fitting protocols. We fit the toxic load model using the constant-concentration data and then used the fitted parameters to frame the time-dependent extensions to the toxic load model. Constant-concentration exposure data is the type of data that is generally available in the inhalation toxicology literature, so any phenomenological toxicity model probably will need to be parameterized using constant-concentration exposure data for the time being. Our procedure of assessing the predictive performance of the time-varying extensions to the toxic load model using a different data set allowed us to avoid "tuning" the models with the same data used for the original experiments.

Some other ways in which our methodology differs from that of Sweeney et al. include the models we considered, the way we accounted for uncertainty, and the way we treated outliers. Our method of identifying exposure durations that result in poor fits of the toxic load model also differs somewhat from that of Sweeney et al., leading us to somewhat different conclusions.

Findings

We found that the constant-concentration exposure data are fit the toxic load model well for the full set of carbon monoxide exposures from 10 to 60 minutes although the data are sparse near the high and low ends of the exposure-response curve. The constant-concentration exposure data do not fit well for the full set of hydrogen cyanide exposures from 2.3 to 30 minutes although the hydrogen cyanide data fit well for exposures from 10 to 30 minutes. We used the fits to the constant-concentration exposure data to parameterize five proposed extensions of the toxic load model to the case of time-varying exposures. For the hydrogen cyanide exposures, we parameterized the models using the 10- to 30-minute exposure data and evaluated the model extensions using the same subset of exposure durations, although we also explored the sensitivity of our results to the choice of the set of exposure durations.

Our analysis of Sweeney et al.'s data on stair-step and intermittent exposures indicates that all five proposed extensions to the toxic load model have difficulty predicting lethality in rats. We also observed some systematic differences in predictive performance among the five models. In particular, the models that define toxic load as a monotonic function of time tend to over-predict lethality, but the time-averaging models do not consistently over-predict or under-predict rat lethality.

Although some of the five models perform better than others with particular data sets, all the models, when parameterized by the constant-concentration exposure data, show statistically significant systematic prediction biases on an individual profile-by-profile basis, and none of the models predict rat lethality within the bounds expected by small sample size errors. Furthermore, no one model appears to be clearly superior across both the hydrogen cyanide and carbon monoxide data sets. Consequently, although the toxic load model is thought to be a good phenomenological toxicity model, we urge caution within the hazard prediction modeling community when selecting and applying extensions of this model. We also recommend caution when applying this model to exposure durations shorter than 10 minutes, at least for hydrogen cyanide. Further work likely will be necessary to determine whether the toxic load model is "good enough" for specific hazard prediction modeling applications.

It is difficult to quantify how failures of toxicological models will affect hazard prediction modeling. The impact of an inaccuracy in the toxicological model will depend on the nature of the hazard event. For example, errors at the low end of the exposure-response curve (e.g., below 10 percent of the population responding) could result in large errors in the predicted size of the hazardous area, whereby edges typically consist of long spatial tails of low concentrations. The significance of errors in the predicted size of the hazardous area in turn depends on where the at-risk population is located.

Potential Approaches to Modeling Inhalation Toxicity

Our results raise the question of how best to model the toxic effects of acute inhalation exposures for the complex time-varying atmospheric concentration profiles characteristic of real-world airborne toxic release incidents. Real-world atmospheric concentration profiles are much more complex than the idealized laboratory profiles explored by Sweeney et al. and by Saltzman and Fox (1986). They may be composed of fluctuations that span several timescales and contain intermittent periods of various durations; total exposure durations may range from minutes (or shorter) to tens of minutes (or longer). A practical toxicological modeling approach—whether simple or complex—should be robust across the range of relevant exposure durations and profile shapes. We explored several potential approaches to modeling the effects of real-world inhalation exposures and came up with the following suggestions:

- Future research would benefit from closer collaboration between the toxicology community and hazard prediction modelers in the military, intelligence, emergency response, environmental regulation, chemical process safety, and transportation safety communities;
- Further research is needed to determine the answer to whether it is possible to build accurate and practical models for time-varying inhalation exposures that have reasonable data requirements; and
- Further development of the toxic load model is not warranted at this time.

We recommend that any new toxicological research in this area focus on theoretical efforts to develop new toxicological models, coupled with exploratory experiments to help develop the form of the models, experiments to determine the biologically based parameters for the models, and experiments to validate the models using laboratory exposures that are representative of real-world atmospheric exposures. Relevance to hazard prediction modelers should be considered throughout this effort from beginning to end. Any comprehensive effort to build new models should bring together theoretical toxicologists, experimental toxicologists, and hazard prediction modelers to guide each other's work.

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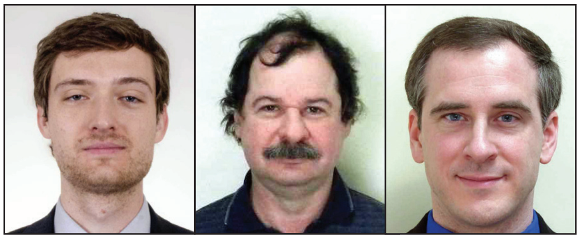

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Agreed Competition in Cyberspace[1]

Michael P. Fischerkeller and Richard J. Harknett

Two strategic games are possible with cyber operations and campaigns, each with different rules and dynamics. The United States has focused almost exclusively on the strategic game of armed conflict in the cyber domain, while many states are playing the strategic game of competition. Recognizing the differences between armed conflict and competition is essential to maintaining strategic stability in cyberspace.

Introduction

Pursuing U.S. objectives in the operational domain of cyberspace requires strategies that can succeed in armed conflict and the competitive space short of armed conflict. Arriving at acceptable behavioral norms requires explicit bargaining in the strategic space of armed conflict. But a tacit bargaining approach is the better starting point for producing mutual understandings of acceptable and unacceptable behavior in the competitive space short of armed conflict. Empirical evidence suggests that a form of *tacit agreed competition* is ongoing in this competitive

Agreed competition is a unique, structurally derived and defined phenomenon of cyberspace that allows for a better understanding of the cyber strategic competitive space short of armed conflict.

[1] Based on M. P. Fischerkeller and R. J. Harknett, “What Is Agreed Competition in Cyberspace?” *Lawfare*, February 19, 2019, https://www.lawfareblog.com/what-agreed-competition-cyberspace.

space. In this essay, we explain the logic of agreed competition in the cyber operational domain.

Defining Agreed Competition

We have argued that a strategy of deterrence for cyberspace is appropriate in the strategic space of armed conflict but that a strategy of persistent engagement is more appropriate in the cyber strategic competitive space short of armed conflict (see Fischerkeller and Harknett 2017). Strategic escalation, through threat or action, can provide an advantage in limited conflicts, according to Herman Kahn (1965). In limited conflict, deterrence is only as effective as the threat of escalation is credible. Deterrence is combined with the threat of escalation to achieve escalation dominance—the condition in which an adversary's response must be either to accept the status quo or to back down. Coercive escalation strategies like those developed by Kahn are viable in the strategic space of armed conflict, including cyber, due to the nature and threat of war.

Kahn described another way adversaries could seek to gain strategic advantage in conflict—by making use of factors associated with a particular level of escalation he called *agreed battle*. Agreed battle manifests when adversaries have strategic rationales to not escalate. Agreed battle does not imply a shared understanding, an intention of indefinite containment, or even a conscious quid pro quo arrangement. The concept combines the range of conflict agreed upon and the acceptable and unacceptable behaviors within that conflict space. Interactions between adversaries are necessary to reach agreement on these conditions. The way to gain strategic advantage is by adopting an approach within the battle's structural boundaries. The resulting dynamic is competitive interaction within those boundaries, rather than spiraling escalation into new levels of conflict.

With the concept of *agreed competition*, we have refined Kahn's concept of agreed battle to better align with the cyber strategic competitive space short of armed conflict. Behaviorally, cyber actors appear to have tacitly agreed on the bounds of this space as being between operational inactivity and operations just short of what would generate the cyber equivalent of armed attack. The strategic dynamic that follows from continuous cyber operations, then, is competitive interaction within agreed competition's boundaries, not escalation out of them.

The tacit agreement over the substantive character of acceptable and unacceptable behaviors within agreed competition's boundaries is still being formed. The United States has not agreed, for example, that China's theft of intellectual property and personally identifiable information is acceptable behavior. The United States is in the early stages of an agreed competition with China in which the structural boundaries are tacitly understood, but mutual understanding of acceptable and unacceptable behaviors are still being developed through competitive interaction. We expect that a more active U.S. strategy of persistent engagement will help define the character of acceptable cyber competition and differentiate it from cyber armed conflict.

Advantages of Adopting the Agreed Competition Concept

Kahn's mechanisms of escalation (i.e., widening the area, compounding, and intensifying) can be repurposed so that an operational objective of persistent engagement is to inhibit an adversary's attempts at the same. Persistent engagement can inhibit adversary campaigns that seek to increase the number of systems affected (widening cyber); the number of actors affected or implicated as causing an effect (compounding cyber); and increase the frequency, duration, level, and visibility of effects (intensifying cyber).

This framework highlights three concerns regarding the stability of agreed competition:

1. Some states may seek to legitimize significantly disruptive cyber actions or operations short of armed conflict while the substantive character of agreed competition is still maturing.

2. Differing perspectives about types of acceptable campaigns or operations introduce avenues for unintended escalation out of agreed competition. Such uncertainty will affect both actors with harmful intent and states exploring this competitive space with defensive objectives.

3. Imbalances in outcomes of long-term competitive interactions will produce shifts in relative power that may lead to instability; when a state experiences a decline in power and senses rising competitors, the incentive for deliberate escalation into armed conflict increases.

All significant actors face challenges in agreed competition, and clarifying these challenges would help ensure stability. Seeing the strategic competitive space as agreed competition highlights the strategic pitfalls of advancing interests too assertively and highlights areas that require further study. Adversaries in this competitive space have mutual interests in avoiding escalation to violent conflict, and these interests could be the basis for explicit or tacit bargaining in support of stability.

Agreed Competition does not Apply to Other Military Operating Domains

The land, maritime, and air military operational domains share the same core structural feature—segmentation (see Fischerkeller and Harknett 2017). Segmentation derives from states exercising their sovereign rights within recognized boundaries. When states move out of the space short of armed conflict into open war, sovereignty is violated, and those domains become connected temporarily. However, in non-conflict situations, segmentation is the enduring structural feature of the land, maritime, and air domains. The military operating domain of space is different because space is accepted as commons by international agreement, meaning that space is not subject to national appropriation by claim of sovereignty. However, the absence of sovereignty-derived segmentation in space does not imply structural interconnectedness. National systems operate within the commons without connection to each other.

Segmentation does not produce a structural disincentive to escalate in these domains. It results in a condition of episodic contact, during which the incentivize is to use escalation as the strategic approach. Land, maritime, air, and space capabilities reflect this; they are designed and developed to coerce and deter, and, should that fail, to prevail in conflicts through threats of or actual escalation in uses of force. National interests in these domains can be advanced by holding capabilities in reserve or holding at risk (on the basis of prospective threat). These actions would not apply in a cyber strategic competitive space short of armed conflict, which demands persistence.

Agreed Competition is not the Same as Gray Zone Challenges

Kapusta (2015, 20) defines gray zone challenges as "competitive interactions among and within state and non-state actors that fall between" traditional, declared war and peace, and that "are characterized by ambiguity about the nature of the conflict, opacity of the parties involved, or uncertainty about the relevant policy and legal frameworks." The definition seems to include cyber operations, but because it describes challenges, not a strategic space, a straightforward comparison with agreed competition is inappropriate. The definition could, however, suggest a description of a *multidomain gray zone strategic space*. To explore a structurally based apples-to-apples comparison, we examine how that space would be characterized.

One difference is that a gray zone strategic space would be bounded by peace at one end and traditional, declared war at the other. The tacit structural upper bound characterizing the agreed competition in cyberspace is exclusive of and below operations that generate effects equivalent to those of an armed attack. A typical gray zone operation cited by the literature is the invasion and occupation of the Dominican Republic in 1965–1966. The operation involved more than 40,000 U.S. troops, significant armed attacks, and tragic loss of life. These actions fall within the defined range of actions in the gray zone strategic space, but not the agreed competition framework for cyber strategic competitive space short of armed conflict.

Another difference is that segmentation, not constant contact, is the core structural feature of a multidomain gray zone strategic space. The gray zone literature notes that nation-states made deliberate choices during the Cold War to engage in gray zone activities. At that time, U.S. responses were governed by the rules of state-to-state relations—the same principles of sovereignty that structure the land, maritime, air, and space domains today. This suggests a condition of episodic contact, a strategic approach of escalation, and a strategic dynamic of an escalation ladder.

The literature also notes that nations today are interconnected in unprecedented ways and the velocity of technological change portends an expansion of gray zone challenges. We believe that cyber operations could represent that expansion. The important consequence is that the interconnectedness that is central to technological change has brought forth an entirely novel cyber strategic competitive space short of armed conflict—agreed competition—the features of which lead to equally novel operational prescriptions and strategic concerns.

Agreed Competition and the Return of Great Power Competition

The main focus of current U.S. national security strategy is countering the strategic struggle between great powers in the political, economic, and military arenas (White House 2017, 27; Department of Defense 2018, 1–2). The agreed competition framework has important implications for this anticipated return of great power competition.

If the comprehensive great power competition were viewed structurally as a comprehensive *strategic competitive space* (as we did with the gray zone), it would share the following characteristics of cyberspace's agreed competition: tacit agreement on structural bounds and a rationale to seek strategic advantage short of armed conflict. However, it would not share the structural disincentive to escalate because it would not share the core structural feature of interconnectedness from which the disincentive ultimately derives. Moreover, a comprehensive great power competitive space would comprise all military domains, multiple sectors, and every instrument of national power, making it far more expansive than the competitive space characterized as agreed competition. Agreed competition should be understood as a component of the great power competitive space with its own distinct structural features, incentives, and dynamic.

Conclusion

Agreed competition is a unique, structurally derived and defined phenomenon of cyberspace that allows for a better understanding of the cyber strategic competitive space short of armed conflict. It helps explain the observed behavior of actors competing in the space and has implications for the strategies they are likely to employ. This framework is unique to the cyber domain because other operating domains do not share cyberspace's core structural feature of interconnectedness. Agreed competition does not characterize gray zone challenges, nor is it applicable to any reasonable description of multidomain gray zone competitive space. Further, it has only limited application to a comprehensive strategic global competitive space.

Managing cyber operations short of armed conflict should advance national interests while enhancing cybersecurity and global stability. To do that, we must understand the strategic environment in which the operations are being conducted. The concept of agreed competition allows for robust academic and policy analysis that can support the evolution of this increasingly critical international security domain into a stable arena of global politics.

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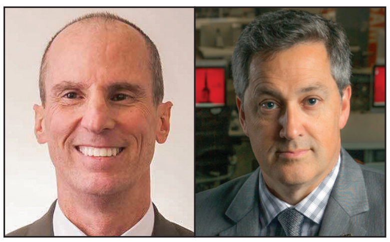

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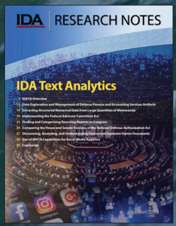

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