

Summer 2020

AERONAUTICS

The

BRIDGE

LINKING ENGINEERING AND SOCIETY

Aeropropulsion: Advances, Opportunities, and Challenges

Alan H. Epstein

**Hybrid Electric Aircraft to Improve
Environmental Impacts of General Aviation**

Jean J. Botti

Electrified Aircraft Propulsion

John S. Langford and David K. Hall

Supersonic Flight and Sustainability: A New Horizon

Raymond Russell, Lourdes Maurice, and Rachel E. Devine

Embracing the Risk Sciences to Enhance Air Travel Safety

B. John Garrick and Ali Mosleh

Some Steps toward Autonomy in Aeronautics

John-Paul B. Clarke and Claire J. Tomlin

**Flying at the Edge of Space and Beyond:
The Opportunities and Challenges of Hypersonic Flight**

Kevin G. Bowcutt

**Aerospace Prizes Inspire the Five I's of Success:
Imagination, Invention, Innovation, Investment, and Impact**

Darryll J. Pines

EES Perspective:

Ethical Decision Making and the Aviation Industry

Elizabeth A. Hoppe

**Putting Out Fire ... with Gasoline?
A Pragmatic Path toward Clean Fuels**

Nicholas C. Margiewicz

NATIONAL ACADEMY OF ENGINEERING

The mission of the National Academy of Engineering is to advance the well-being of the nation by promoting a vibrant engineering profession and by marshalling the expertise and insights of eminent engineers to provide independent advice to the federal government on matters involving engineering and technology.

The BRIDGE

NATIONAL ACADEMY OF ENGINEERING

Gordon R. England, *Chair*
John L. Anderson, *President*
Corale L. Brierley, *Vice President*
Julia M. Phillips, *Home Secretary*
James M. Tien, *Foreign Secretary*
Martin B. Sherwin, *Treasurer*

Editor in Chief: Ronald M. Latanision
Managing Editor: Cameron H. Fletcher
Production Associate: Penelope Gibbs

The Bridge (ISSN 0737-6278) is published quarterly by the National Academy of Engineering, 2101 Constitution Avenue NW, Washington, DC 20418. Periodicals postage paid at Washington, DC.

Vol. 50, No. 2, Summer 2020

Postmaster: Send address changes to *The Bridge*, 2101 Constitution Avenue NW, Washington, DC 20418.

Changes of address or requests to unsubscribe should be sent to PGibbs@nae.edu.

Papers are presented in *The Bridge* on the basis of general interest and timeliness. They reflect the views of the authors and not necessarily the position of the National Academy of Engineering.

The Bridge is printed on recycled paper. ♻️

© 2020 by the National Academy of Sciences. All rights reserved.

Mission Statement of *The Bridge*

The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. Invited guest editors, who have expertise in a given issue's theme, are asked to select authors and topics, and independent experts are enlisted to assess articles for publication. The quarterly has a distribution of about 7,000, including NAE members, members of Congress, libraries, universities, and interested individuals all over the country and the world. Issues are freely accessible at www.nae.edu/Publications/Bridge.aspx.

A complete copy of *The Bridge* is available in PDF format at www.nae.edu/TheBridge. Some of the articles in this issue are also available as HTML documents and may contain links to related sources of information, multimedia files, or other content.

The

Volume 50, Number 2 • Summer 2020

BRIDGE

LINKING ENGINEERING AND SOCIETY



President's Perspective

3 **Microscopic Assault on Humanity**

John L. Anderson

Editor's Note

5 **Looking to the Future in These Challenging Times**

Ronald M. Latanision

Guest Editors' Introduction

6 **Aeronautics: Back to the Future**

Alton D. Romig Jr. and John J. Tracy

Features

8 **Aeropropulsion: Advances, Opportunities, and Challenges**

Alan H. Epstein

Civil aviation faces both exciting opportunities for advancement and growth and daunting environmental challenges.

15 **Hybrid Electric Aircraft to Improve Environmental Impacts of General Aviation**

Jean J. Botti

Advances are needed in battery technology and certification to enable hybrid electric aircraft.

21 **Electrified Aircraft Propulsion**

John S. Langford and David K. Hall

The potential benefit of electrified aircraft propulsion is the flexibility it brings to the aircraft design space.

28 **Supersonic Flight and Sustainability: A New Horizon**

Raymond Russell, Lourdes Maurice, and Rachel E. Devine

The incorporation of sustainability in aircraft design may be precisely what enables the global acceptance and successful return of supersonic transportation.

34 **Embracing the Risk Sciences to Enhance Air Travel Safety**

B. John Garrick and Ali Mosleh

Advanced quantitative risk assessment methods can provide near-term added value to the safety and economic performance of air travel.

43 **Some Steps toward Autonomy in Aeronautics**

John-Paul B. Clarke and Claire J. Tomlin

Advances in technology, computing, and AI point the way forward for the incorporation of greater autonomy in aviation.

| | |
|--|---|
| 51 | <p>Flying at the Edge of Space and Beyond: The Opportunities and Challenges of Hypersonic Flight <i>Kevin G. Bowcutt</i></p> <p>Hypersonic flight may one day enable same-day round-trip global travel.</p> |
| 59 | <p>Aerospace Prizes Inspire the Five I's of Success: Imagination, Invention, Innovation, Investment, and Impact <i>Darryll J. Pines</i></p> <p>Challenge humankind to do something extraordinary, offer a handsome cash incentive, and people may surprise you.</p> |
| 66 | <p>EES Perspective: Ethical Decision Making and the Aviation Industry <i>Elizabeth A. Hoppe</i></p> <p>Commercial aviation is a complex industry that requires strong ethical decision-making skills to maintain safety.</p> |
| 70 | <p>Putting Out Fire ... with Gasoline? A Pragmatic Path toward Clean Fuels <i>Nicholas C. Margiewicz</i></p> <p>Current innovations show that emissions elimination is feasible and does not have to be prohibitively expensive.</p> |
| 76 | <p>An Interview with... Lisa Eastep, Metallurgist and Roller Derby Competitor</p> |
| <p style="text-align: center;">News and Notes</p> | |
| 84 | NAE Newsmakers |
| 86 | NAE Chair, Home Secretary, and Councillors Elected |
| 87 | NAE Honors 2020 Draper Prize Winners |
| 88 | Acceptance Remarks by C. Grant Willson |
| 90 | NAE Director of Programs Elected to AIMBE College of Fellows |
| 90 | Calendar of Meetings and Events |
| 91 | In Memoriam |
| 93 | <i>Invisible Bridges</i> : Interface Value |

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. John L. Anderson is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Acad-

emy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at www.nationalacademies.org.

President's Perspective

Microscopic Assault on Humanity



John L. Anderson,
President, NAE.

Photo credit: Cable Risdon.

In H.G. Wells' *War of the Worlds*, the narrator discovers that the invading Martians have been "slain by the...disease bacteria against which their systems were unprepared;...slain, after all man's devices had failed, by the humblest things that God, in his wisdom, has put upon this earth."¹

In a matter of weeks earlier this year humanity was brought to its knees by 0.1 micrometer colloidal particles with no intelligence as we know it. The covid-19 pandemic should bring some humility to *homo sapiens*, and a recognition of the need for public health on a global rather than national scale.

Because pandemics represent complex systems, engineers play an important role in all phases of reducing the threat, and especially in restoring the physical, social, and economic health of our nation and the world. This point was eloquently made in a *Wall Street Journal* op-ed by the NAE's Director of Programs and Norman R. Augustine Senior Scholar Guru Madhavan.²

Engineers are making contributions in diagnostics, therapeutics, vaccines, protective equipment, medical devices, and supply chain robustness—on a global scale. Much of the work is being done in the private sector as small companies and large corporations research and develop products and scaled-up processes to address specific challenges associated with the pandemic.

A unique feature of this mobilization is the international cooperation among businesses, universities,

government agencies, and philanthropists. An excellent takeaway from this experience would be to preserve such coalitions in preparation for the next pandemic or other crisis, so we can be proactive instead of reactive.

The NAE itself prompted the formation of dynamic coalitions through its Call for Engineering Action,³ engaging cross-disciplinary and cross-generational members of the engineering community in sharing knowledge, skills, systems approaches, and an innovative mindset to combat the contagion and its impact. The project provides a mechanism to bring together people with great ideas and has attracted hundreds of teams.

The National Academies are playing significant roles in combating covid-19 through a newly created Standing Committee on Emerging Infectious Diseases (SCID⁴) as well as focused studies through the normal processes of the National Research Council (NRC). The SCID was formed to provide expert responses, based on information readily available, to queries about the virus and its spread from the White House's Office of Science and Technology Policy. The committee has access to expertise not only among its members but also in subcommittees involving members of all three Academies. In addition, the NRC is accelerating its work to provide consensus studies on a 6-month or faster time scale.

Through these processes, the National Academies are learning how to respond to national needs several times faster than in the past with the same rigorous standards of evidence-based findings and recommendations. This is one example of a lesson learned from the pandemic.

The constraints on movement and gatherings to halt the spread of covid-19 are teaching us something about communications. We are finding that virtual meetings are a partial substitute for in-person meetings when travel is restricted, and they will continue to yield some

³ <https://www.nae.edu/230195/Call-for-Engineering-Action-on-the-COVID19-Crisis>

⁴ <https://www.nationalacademies.org/our-work/standing-committee-on-emerging-infectious-diseases-and-21st-century-health-threats>

¹ Wells HG. 1898. *The War of the Worlds*. London: Heinemann Publishing.

² "The Covid Recovery Comes Down to Engineering," May 5.

savings of time and money in the future. However, we must remember that in-person meetings create human bonding and provide an atmosphere for honest verbal exchange that probably cannot be completely duplicated in virtual settings.

The lockdowns of our communities were painful, and the process of reopening them will be more challenging. We will need to address not only physical health

but also social, mental, and economic health. To do this right will take collaboration among engineers, physical and medical scientists, social scientists, and politicians. The engineering profession will respond to the call. We are in this together.

A handwritten signature in blue ink, appearing to read "John", positioned below the text on the right side of the page.

Editor's Note



Ronald M. Latanision (NAE) is a senior fellow at Exponent.

Looking to the Future in These Challenging Times

It is not often that both the NAE president and executive officer appear simultaneously in an issue of *The Bridge*, but this is just such an occasion.

In his President's Perspective, **John Anderson** writes about the engineering response to covid-19 and the importance of international coalition building as a means of combating the virus that has taken command of our lives. And this issue on aeronautics is coedited by **Al Romig** and **John Tracy**, both of whom have long aviation histories with Lockheed-Martin and Boeing, respectively. From hypersonic vehicles and autonomy in aircraft applications to risk analysis and workforce concerns, the articles explore both considerable progress and next steps in aeronautics.

In this issue we also introduce the youngest writer to submit a manuscript and be published in *The Bridge*. Nicholas Margiewicz is a rising senior at North Port High School in Florida. I met Nick by email through one of his teachers, Teresa Caracciolo, who is chair of the Science Department and was a participant in a summer program that I founded at MIT in 1989, the Science and Engineering Program for Teachers. SEPT continues today, more than 30 years later, and I enjoy regular communication with many of the teachers who joined us in Cambridge.

As a journalism project Nick and his teacher, Brooke Kenner, agreed that he would write a series of articles, entitled "A Highway to the Future," for the school newspaper, *Bobcat Nation*. Nick describes himself as an

environmentalist car enthusiast, which is not too surprising given his age. I remember being a high school junior and while environmental issues were not on my mind at that point, I was then and remain today a car enthusiast.

Nick is interested in "the balance between internal combustion engine-powered transport (with renewable, emissions-free fuels, of course) and electric/hydrogen/etc.-powered transport alongside personal transport and public transport, as well as the need for research in addressing nonexhaust emissions in everything from tires to brakes to refrigerants, and even new ways to strip/remove asbestos in older car parts...."

I do like the approach that Nick is taking. I also feel strongly that we should encourage young, thoughtful people to write for our readership. Nick is already a dynamic thinker and writer! His generation needs to become involved in addressing the issues facing our nation and the world. They will vote in a few years and that may be the important path forward for the US and the planet.

My reading over the past few months leads me to the view that covid-19 and climate change are not mutually exclusive. The world's atmosphere has responded positively as humans have reduced driving and energy consumption. And particulate emissions from various energy sources appear to have a potential role in the nature of the infections that have occurred among the world's population. The planet is telling us something about its resilience. It would be a loss not to recognize this and develop a path forward. I consider Nick's generation crucial to our future, and I welcome hearing from other up-and-coming thinkers and engineers.

Our next issue revisits nuclear electric generation, with **Mike Corradini**, Jacopo Buongiorno, John Parsons, and David Petti as coeditors. The invited articles will look at a future that includes reduced emissions and decarbonization in the energy spectrum.

As always, I welcome your comments and feedback at rlatanision@exponent.com.

A handwritten signature in black ink that reads "RM Latanision". The signature is written in a cursive, slightly slanted style.

Guest Editors' Introduction

Alton D. Romig Jr. and John J. Tracy



Al Romig



John Tracy

Al Romig (NAE) is NAE executive officer and former vice president and general manager of Lockheed Martin Aeronautics Company Advanced Development Programs, better known as the Skunk Works®. John Tracy (NAE) is retired chief technology officer and senior vice president of engineering for the Boeing Company.

Aeronautics: Back to the Future

It has been 16 years since *The Bridge* last focused on aviation (fall 2004). Since then aviation has witnessed significant advances in propulsion, structure, and guidance, navigation, and control, to name just a few areas. There is even renewed interest and considerable momentum toward supersonic and hypersonic vehicle design concepts.

It should be noted, though, that all of this work is being accomplished during a period when 30–40 percent of the aviation/aerospace workforce is eligible to retire in the next 5 years, creating a huge need to inspire and train the next generation of engineers (Hedden and Sands 2019).

Background

Commercial aviation is responsible for between 5 and 8 percent of the world's gross domestic product. The aviation ecosystem employs millions of people around the world (FAA 2016). And aviation continues to grow in technical sophistication and popularity as average incomes rise and international trade touches every corner of the planet.

Furthermore, aviation remains by far the safest form of transportation in terms of passenger-miles traveled (Ferro 2018). When there is an accident, however, it is dramatic and raises concerns. Two deadly crashes of the Boeing 737 MAX in 2018 and 2019 garnered much attention and brought the topic of aviation safety to the

fore in discussions throughout the world. The impacts and lessons learned continue to reverberate.

In addition, public concern about climate change now regularly includes the role of aviation. Manufacturers and operators are heeding the call for more environmentally sustainable designs and fuels.

In This Issue

Since the beginning of the jet age in the mid-1950s, fuel efficiency has increased by over 70 percent and in general continues to improve about 1 percent a year. Aerodynamics, structures, materials, and propulsion all play into this improvement, but none more than advances in gas turbine engines. Movement toward higher bypass ratio engines has driven the performance of the industry to levels that were previously unimagined. **Alan Epstein** reviews advances in aerodynamics, thermodynamics, design, materials, and manufacturing that are enhancing engine performance, life, safety, and efficiency. He also discusses propulsion challenges related to supersonic flight, electrification, and sustainability.

Motivated by the need to improve even further in the areas of safety and the environment, exciting work is being conducted in hybrid and fully electric propulsion. Both of these areas offer great promise over longer time horizons and various use cases. As with any new technologies, there have been many more discussions of the potential benefits than there have been of the technical and cost constraints. **Jean Botti** lays out the benefits and the challenges for hybrid propulsion approaches,

considering battery energy density, durability, charging, safety, and pilot training.

All-electric propulsion has received a great deal of attention, catalyzed by the growth in electric automobiles. The general public has seen numerous popular accounts of flight-based “ride-sharing services” using all-electric propulsion. **John Langford** and David Hall explore the benefits and challenges of electrification in an analytical assessment of specific all-electric configurations. They also look at some particularly interesting distributed propulsion approaches not readily available for gas turbines as well as required battery energy density, fuel cells, and solar power.

Despite substantial reductions in fuel burn and, in turn, CO₂ production, aviation is still a measurable contributor (~2 percent) to greenhouse gases. The desire to return to supersonic air travel is dampened by concerns about its environmental impact and noise. Raymond Russell, Lourdes Maurice, and Rachel Devine discuss these concerns in the context of progress since the Concorde. They describe advances in aerodynamic design, engines and turbofans, materials, and sustainable fuels as well as operational changes, all of which improve fuel burn and reduce noise.

Like the environment, safety is an area of great interest to both the aviation specialist and the general public. Air transportation has actually seen orders of magnitude improvement in safety over the past half-century (Allianz 2014) because every accident and near miss is investigated to its root cause in a joint effort between industry and government regulators. As aviation systems become more complex and have human, ground, and in-air components, the safety and risk analysis of these systems also become more complex. **B. John Garrick** and **Ali Mosleh** discuss quantitative risk-based approaches that take account of this complexity, data limitations, performance-influencing factors that affect pilot decision making, and the key enablers of hardware, software, and modeling. Specific applications discussed include collision avoidance, accompanied by analysis of a 2002 midair collision.

As automation increasingly permeates daily life, its impact on aviation safety requires thoughtful consideration. J-P. Clarke and **Claire Tomlin** provide baseline definitions of autonomy for aircraft applications and review safety aspects of autonomy, describing the use of human-machine teaming, neural networks for flight management, the loyal wingman program, and run-time assurance. They also touch on the highly anticipated possibility of urban air mobility.

The prospect of being able to fly from New York to London in 45 minutes is sure to get the attention of business travelers and the public. Hypersonic aviation offers the promise of such travel. But with that promise come some of the most significant technical challenges that the industry has ever faced. **Kevin Bowcutt** reviews the motivation for hypersonic flight, progress to date, and the challenges going forward in design, materials, fuels, costs, noise, regulation, and impacts on the environment.

The progress described in these articles resulted from the hard work of generations of engineers both in the United States and around the world. But the aeronautics engineering workforce is now at a crossroads. In 2019, 30 percent of its employees were over 55 years of age. Over the next few years there is a very real risk that more people will voluntarily leave the industry for retirement than can be replaced with new graduates. The need is clear to improve ways to inspire and educate the future workforce. **Darryll Pines** surveys the history and importance of prize-based competitions in the critical success factors of imagination, invention, innovation, investment, and impact as related to advances in aerospace. His examples illustrate the attractiveness of such competitions to innovators of all ages.

Finally, we thank the following, who were asked to evaluate the accuracy, coverage, and substantiation of these articles: Juan Alonso, **John D. Anderson**, Karl Bilimoria, Marty Bradley, Gillian Bussey, Nicholas Cumpsty, Brian German, **Edward Greitzer**, Jonathon How, **Keoki Jackson**, Jeff Lenorovitz, Charles Leonard, Muni Majjigi, Dimitri Mavris, **Roger L. McCarthy**, and Hamid Shirazi.

The articles in this issue present the scope of progress and possibility in modern aviation. Challenges are being addressed through innovative developments that will support and enhance air travel in the decades to come. We welcome your feedback on this aviation-focused issue.

References

- Allianz. 2014. *Global Aviation Safety Study*. Munich: Allianz Global Corporate & Specialty SE.
- FAA [Federal Aviation Administration]. 2016. *The Economic Impact of Civil Aviation on the US Economy*. Washington.
- Ferro S. 2018. Fear of flying? Airplanes are, in fact, the safest way to travel. *Mental Floss*, May 9.
- Hedden CR, Sands C, eds. 2019. *2019 Workforce Data Pinpoints Need for Tailored Recruiting as Job Requirements Boom*. New York: Aviation Week Network.

Civil aviation faces both exciting opportunities for advancement and growth and daunting environmental challenges.

Aeropropulsion: Advances, Opportunities, and Challenges



Alan Epstein (NAE) is the RC Maclaurin Professor emeritus at the Massachusetts Institute of Technology and former vice president of technology and environment at Pratt & Whitney.

Alan H. Epstein

This is an exciting time of both opportunities and challenges for civil aeronautics. Opportunities include dramatic reductions in aircraft noise and the development of drones of all sizes and shapes, air taxis, and low-boom supersonic travel. Challenges include the need for new technologies and materials to improve efficiency, noise, engine-airframe integration, and, importantly, environmental concerns, especially those associated with climate change. Underlying all is aviation's imperative of increased safety. Propulsion technology is one key to both the opportunities and the concerns.

Background

The span of aeronautical system size and capability is enormous. Air vehicles now range from 1 kg drones that fly for a few minutes to 500,000 kg airliners that travel halfway around the planet.

The power and energy needed to enable these capabilities vary widely (figure 1), as do the technologies that propel them. Small autonomous aerial vehicles are electric and need only a few hundred watts of power. Small helicopters such as an R22 require about 100 kW, similar to an automobile, and are powered by internal combustion engines. A large airliner needs hundreds of MW, a power level now feasible only with gas turbines. Vehicle energy needs vary even more: a small drone may fly on flashlight batteries, an airliner may take off with 10,000 times more energy than a Tesla S car. Propul-

sion opportunities and challenges exist across this size range.

Modern Jet Engines

Most of the world's aerospace industry's \$800 billion-per-year manufacturing and maintenance economic activity is associated with jet-powered commercial aviation. Engines represent about 20 percent of the value of a new airplane and account for about 14 percent of total operating costs of short-range airlines and up to 28 percent for long-range airlines.

Performance, life, and safety improvements in airliner jet engines depend on massive investments in technology coupled with increasingly sophisticated design, as well as painstaking attention to detail and to system integration. Practical improvement requires reduced aerodynamic losses, increases in compressor pressure ratio, and higher turbine inlet temperature.

Engine efficiency, reliability, and weight are major determinants of airliner capability and cost. There is as much still to be gained in jet propulsion as has been achieved in the last 70 years of engine development. This will require investments in advanced technology, materials, and design.

Engine Efficiency and Reliability

Since the introduction of turbojet-powered airliners in the late 1950s, engine efficiency and reliability have increased severalfold. In today's airliners, powered by simple Brayton cycle engines driving ducted fans, thermal efficiency at cruise (the conversion of fuel chemical energy into shaft work) has increased from about 20 percent to 55 percent, and propulsive efficiency (defined here as the conversion of shaft work to work useful to propel the aircraft) has increased from about 40 percent to over 70 percent. Overall efficiency has about doubled, to 40 percent.

The shaft power needed to drive fans or propellers can be generated in many ways. Simple Brayton cycles have proven the most efficient and economical, although more complex cycles have been and are still extensively studied. The theoretical efficiency of an ideal Brayton cycle at airliner cruising altitudes is over 80 percent, but the industry consensus is that overall efficiencies approaching 60 percent may be possible (Epstein 2014).

One measure of reliability, the in-flight shutdown rate, has improved by a factor of 1,000 from the early 1960s. At current levels of 0.5 engine shutdown per

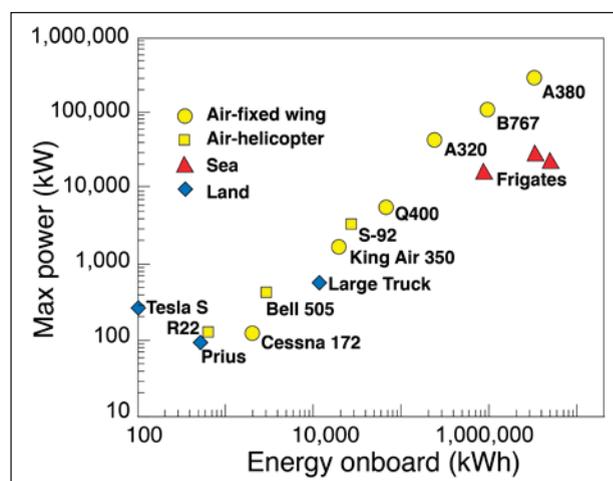


FIGURE 1 Maximum vehicle power and energy. Compared to a Tesla S car, an airliner needs 1,000 times more power and 10,000 times more energy. The energy on board a large airliner is equivalent to more than 1,000 tons of TNT. Adapted from Epstein (2014).

million flight hours, most commercial pilots will never need to shut down an engine.

Engine Weight

Engine efficiency and maintenance cost can be traded against engine weight.¹ Reducing engine weight or fuel burn means an airplane can be lighter and therefore less expensive to produce and operate, or it can fly farther at the same weight thereby opening up new routes.

The power-to-weight ratio of engines has only doubled, because economics have favored improved efficiency, reliability, and life over weight. As engine efficiency has improved, the hot parts have shrunk (higher efficiency and higher pressures reduce the hot flow areas needed) but the cooler fan-related parts have increased in size, generating weight challenges.

Recent Advances

There has been much progress in fundamental understanding and in design tools for structural modeling, turbomachinery aerodynamics, combustion, heat transfer, fracture mechanics, and materials. Combined with new structural materials and coatings, advanced controls, and manufacturing technologies, as well as design innovations such as active clearance control, laminar flow airfoils, and 99+ percent efficient gear systems, the result is quieter, lighter, and more efficient and reliable engines.

¹ Also important for overall aircraft capability are the weight of the structure that supports the engine and the fuel that powers it.

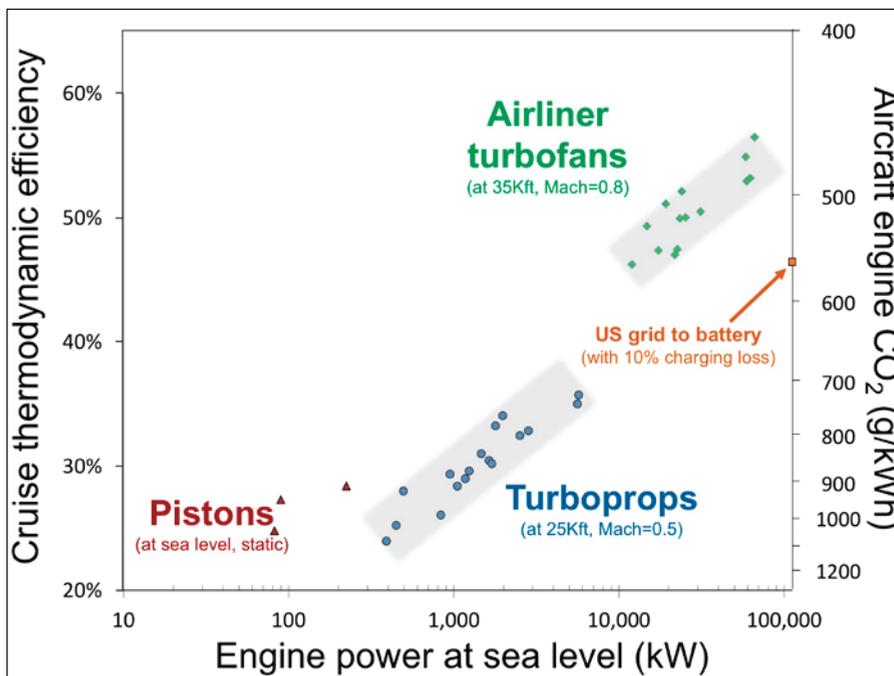


FIGURE 2 Aircraft engine cruise efficiency (left axis) and CO₂ emissions (right axis) at cruise vs. engine power capability. CO₂ from charging a battery off the US grid indicated on right axis. Adapted from Epstein and O’Flarity (2019), grid data from EIA (2018).

With advances in enabling technologies, designers decreased the pressure ratio across the engine fan to reduce engine exhaust velocity and improve propulsive efficiency. Airplane thrust needs and engine thrust capability both vary with flight speed and altitude, by a factor of 3–6, but not necessarily together. Since the thrust of the fan—which provides about 90 percent of the engine’s thrust—is the product of the fan’s exhaust velocity and air mass flow, the fan size must be increased to maintain thrust as its pressure ratio is decreased.

Engine designs are closely tailored for each application to minimize airline total cost. Decreased fan pressure ratio more closely matches engine capability to aircraft needs. One result is that engines are no longer sized by takeoff requirements, as for previous generations, but for thrust at top of climb.

The economics of long-range routes favors fuel consumption over weight and manufacturing and maintenance costs. Large aircraft are optimized for longer routes so engine cruise efficiency typically increases with engine size (figure 2).

Opportunities

Noise Reduction

Aircraft noise is both an environmental impact and a major impediment to the expansion of air transportation: communities typically resist new airports, runways, and flight paths because of noise concerns.

Technology advances have reduced the airliner noise “footprint” area on the ground by a factor of 10 since 1960 (Spakovszky 2019). Historically, the engine exhaust was the predominant noise source. As fan size has increased, the resulting reduction in exhaust velocity has greatly reduced jet exhaust noise. Airliner noise now comes as much from the airframe as it does from the engine, and the fan is the predominant engine noise source on takeoff and landing.

Studies suggest that with a focused research investment over the next decade on airframe and engine noise-related technologies, a virtually silent (i.e., quieter than the urban ambient) large airliner may be feasible with competitive economics (Spakovszky 2019).

Supersonic Commercial Flight

Supersonic commercial flight was a major goal of the 1960s, but the Boeing 2707 was cancelled because of emerging environmental and economic concerns. Production of the rival British-French Concorde was limited to just 16 aircraft, which were exempted from environmental regulations but not the FAA’s ban on civil overland supersonic flight. Current environmental regulations do not apply to supersonic aircraft, but an international regulatory structure is needed before most enterprises will invest the billions necessary to design and certify a new large aircraft.

Acoustic theories developed in the 1980s and ’90s suggest that supersonic aircraft can be shaped to reduce the sonic boom reaching the ground. The NASA X-59 aircraft in development is designed to validate those theories and to generate data on community boom acceptance to inform rulemaking (Kamlet 2019).

Whatever the finding on boom noise, profound challenges still exist for landing and takeoff noise and for emissions, especially CO₂, which will be several times greater per passenger-kilometer than for subsonic jets. All things considered, supersonic commercial flight remains a very hard problem.

Vertical Takeoff and Landing and Urban Air Mobility

Perhaps the most exciting nearer-term opportunities are vertical takeoff and landing (VTOL) small drones of all sizes and shapes and larger passenger-carrying air taxis, also called personal air vehicles or urban air mobility (UAM).

Inventors worked on flying cars for 100 years without notable success, stymied by issues with control and reliability. Such vehicles are now feasible thanks to (i) progress in autonomy, navigation, and control (which are beyond the scope of this article) and (ii) innovations in propulsion.

Modern gas turbines are sufficiently light and reliable, but much too expensive for UAM applications. Electric propulsion might offer the potential for high reliability at lower cost. The short range needed for UAM reduces the importance of the very low energy density of batteries compared to jet fuel. From a propulsion point of view, such vehicles are technically feasible in the next decade, although the economics of these systems have yet to be established.

Electric Propulsion

Electric propulsion presents exciting possibilities. For airliners, the nearest-term possibility is a mild hybrid, with an electric motor reducing the engine power needed for a few minutes near the top of climb, helping during transients, and improving engine optimization.

A 25 MW takeoff-power single-aisle aircraft engine produces about 7 MW at top of climb, and preliminary studies suggest that a 1–2 MW motor could help resize the engine and other aircraft subsystems to save 2–6 percent in fuel and 1–2 percent in energy. This level of savings, however, requires several hundred percent improvements in the weight of current electric motors, drives, and batteries. An aircraft that uses this electric power and energy storage for other functions might improve the attractiveness of these mild hybrid systems (Lents and Hardin 2019).

Multirotor electric propulsion for VTOL offers the advantage of greatly reduced mechanical complexity compared to traditional helicopters, although more

power is needed for the same vehicle footprint. The energy density of rechargeable, high-discharge-rate batteries has more than doubled over the last two decades, and significant progress is expected, driven by land transport applications. Packaged battery energy density is now approaching the level that enables battery-powered UAM vehicles at shorter ranges. (Airliner applications are discussed below.)

An electric motor may reduce the engine power needed for the top of climb and improve engine optimization.

There is also new emphasis on developing lightweight, high-efficiency electric motor technology and power system electronics. The efficiency of current aeronautical engines in the size range of up to 1,000 kW is only 15–30 percent, so battery-powered electric drives are more attractive at this size than for higher-power airline applications (figure 2).

Challenges

Design Validation and Certification

New engines, which consist of 20,000–40,000 parts, are complex devices to engineer. A new 30,000 lb thrust class engine for a single-aisle aircraft currently requires about 50 months and \$1 billion to certify, with the cost roughly evenly split between personnel and the hardware and its testing. A twin-aisle aircraft engine, with three times the thrust, costs about twice that. Benefits in fuel burn and economics of at least 8–10 percent are typically needed to justify the required investment.

Ideally, only the testing needed to validate the design and certify the engine would be done. Currently, however, first principles analyses do not yield solutions of sufficient accuracy to meet design requirements in many areas, so empirical methods backed by more extensive testing are used. Engine testing needs and development cost could be significantly reduced with improved modeling tools, especially for combustor emissions, noise, aeromechanics, compressor stability, and part life.

The large number of parts in an engine and variations introduced in manufacturing and operation have also generated a need for tools capable of moving from

deterministic design practices toward probabilistic approaches.

New Technology and Materials

New technology and materials are needed to advance the state of the art (Epstein 2014). Better thermal efficiency requires structural materials and coatings with improved temperature capabilities and chemical resistance for both compressor and turbine parts. After decades of development, 1300°C-capable ceramic matrix composites are just entering service; research is now focused on 1500°C-capable ceramics.

Titanium-aluminide was introduced in the past decade to reduce weight. The safety and maintenance implications of replacing ductal metals with low-fracture-toughness materials still represents a major challenge. Also, some advanced materials have proven susceptible to corrosion from atmospheric pollution such that the overhaul life of an engine operated in hot areas with poor air quality can be half that of an engine operated in cooler, cleaner air.

The overhaul life of an engine operated in hot areas with poor air quality can be half that in cooler, cleaner air.

The introduction of new material families often requires new manufacturing techniques. In this and other ways, manufacturing technology has a large role to play in both enabling design innovation and reducing cost. For example, the turbine airflow area per unit thrust has decreased by an order of magnitude since 1970, so fabricating increasingly smaller parts at high precision is an ongoing need. Advanced additive manufacturing is increasingly important as precision, internal flaws, and surface finish improve.

Engine-Airframe Integration

Engine-airframe integration is of growing importance as engine diameter grows. The current practice of wing-mounted engine pylons started in the early 1950s with the Boeing B-47. The pylons decoupled the wing aerodynamics from the propulsion system to a degree, but this isolation eroded as fan size increased. Engine

nacelle diameter now approaches that of the fuselage because improving propulsive efficiency requires increasing fan area.

Further area increases could come from either larger fans or more of them. Increasing fan diameter requires technologies that decrease the weight and drag penalties of nacelles and their installation. Another approach is to keep the fan and nacelle diameter small but to increase their number. The maintenance economics that favor two-engine aircraft must be addressed.

Other concepts under study more tightly integrate the propulsion system with the airframe to reduce energy needs. Some, like the so-called D8 “double-bubble,” pass the fuselage boundary layer through the fans to improve the propulsive efficiency for the same fan area (Uranga et al. 2017). Such highly integrated configurations that depart from the traditional tube and wing architectures raise a new realm of technical challenges.

The Climate Change Challenge and Propulsion

Aviation’s most pressing challenge is climate change.

Emissions

CO₂ is the principal anthropogenic driver of climate change. Aviation produces about 2 percent of the world’s man-made CO₂, far less than ground transportation, and modern aircraft require less energy and produce less CO₂ per passenger-kilometer than do cars and trains in the United States. Nevertheless, both the political threat and the need to act are very real. A decade ago, in response to this concern, aviation leaders pledged to reduce aviation’s CO₂ to half that of 2005 by the year 2050. Since air travel is growing by 4–5 percent a year, this is a significant challenge.

CO₂ reduction requires some combination of reducing both the energy needed for flight and the net carbon associated with that energy. If aviation grows as projected, halving its CO₂ by 2050 will require a fourfold reduction, far more than can be expected from aircraft energy-saving technologies. Reducing the carbon intensity of aviation energy must therefore be a major focus of research and development.

More than 95 percent of aviation’s CO₂ is emitted by airliners capable of flying 70 or more passengers thousands of kilometers, and large twin-aisle airliners, which typically fly average stage lengths of 6,500 km, account for over 50 percent (figure 3).² Thus to achieve

² About 90 percent of the CO₂ is emitted on routes longer than 750 km.

the desired global CO₂ reduction, technology is needed for large airliners flying long distances rather than for general aviation or small regional aircraft.

The challenge of low-carbon energy for aviation can be considered in two parts: the source of the energy and the manner in which it is stored on the aircraft. Two choices are electric energy stored in batteries and liquid fuels stored in tanks.

Battery Power

Given that jet fuel has an energy density of 12,000 Wh/kg and the latest long-range aircraft have 55 percent cruise thermal efficiency, the net energy density is 6,600 Wh/kg. Current automotive battery packs are in the 120–180 Wh/kg range, less than 3 percent that of jet fuel. There is no known battery technology that can power large electric airliners.

While there are speculations on electric aircraft configurations that reduce fuel burn, none have been proposed that could not be implemented with fueled engines. There are also significant weight and reliability challenges with multimewatt electric drives. Together, these imply that battery power will not be capable of halving aviation's CO₂ by 2050.

Furthermore, even if there were a scientific breakthrough that enabled a battery-powered airliner, an electric airliner would not reduce aviation's CO₂ because new aircraft engines produce less CO₂ per unit of energy than does the US electric grid (figure 2; Epstein and O'Flarity 2019). Of course, both should improve over time.

Liquid Fuel Alternatives

The only path forward with the technical potential to reduce aviation's CO₂ by factors of 2 to 4 by 2050 is improved aircraft and engines powered by fuel that does not release net CO₂ into the atmosphere. One such fuel is hydrogen, which was first considered for military aircraft propulsion in the 1950s. It proved a poor fuel for high-speed aircraft because its low density and thus large tank volume increases aircraft weight and drag. There are also profound safety challenges for cryogenic aircraft fuels.

The most promising fuel candidates are liquid hydrocarbons known as sustainable alternative jet fuels (SAJFs). They are sustainable because they can save 80 percent or more on CO₂ and not adversely affect food and water supplies; alternative means they are

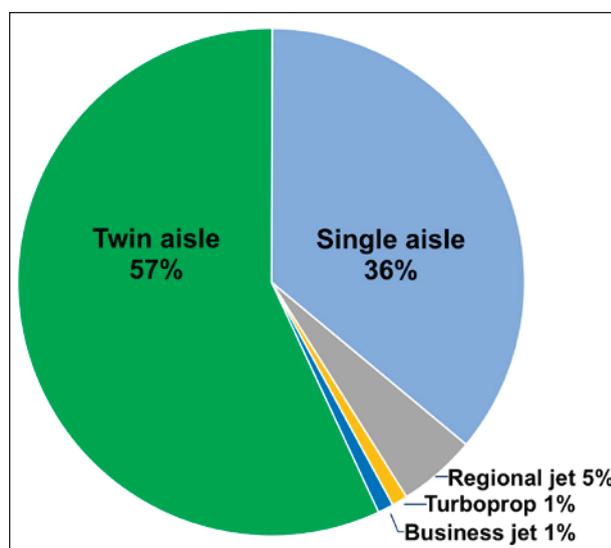


FIGURE 3 World civil aviation jet fuel consumption by aircraft class. More than 93% of the fuel is consumed by aircraft that have the capacity to carry more than 120 passengers and can fly thousands of kilometers. Data from Yutko and Hansman (2011).

compatible with existing aircraft and fuel infrastructure. Several SAJFs have been certified for use and are in limited commercial service (TRB 2019).

SAJFs can be produced by many processes. Those certified to date include biofuels, Fischer-Tropsch fuels manufactured from CO and H₂, and the conversion of alcohol to jet fuel. Much needs to be done to expand their availability. The principal challenges are economic, including capital and feedstock cost. Policy can play a role in shaping aviation's energy supply, but that is beyond the scope of this discussion.

Conclusion

Civil aircraft propulsion faces important opportunities and challenges. Opportunities include the improvement of overall propulsion efficiency from 40 percent to 60 percent, elimination of aircraft noise, and realization of urban air mobility vehicles. Each application is rich in technical opportunities.

Looming over the opportunities is aviation's need to address the challenges of climate change. Given the expected growth rate of civil aviation, the only technically viable approach for reducing aviation CO₂ by a factor of 4 is a switch to a low-carbon energy source, sustainable alternative jet fuels.

References

- EIA [United States Energy Information Agency]. 2018. Electric Power Annual. Washington. Online at <https://www.eia.gov/electricity/annual/pdf/epa.pdf>.
- Epstein AH. 2014. Aeropropulsion for commercial aircraft in the 21st century and research directions needed. *AIAA Journal* 52(5):901–11.
- Epstein AH, O'Flarity SM. 2019. Considerations for reducing aviation's CO₂ with aircraft electric propulsion. *AIAA Journal of Propulsion and Power* 35(3):572–82.
- Kamlet M. 2019. NASA supersonic testing: Streets, suburbs, and sonic booms. *Journal of the Acoustical Society of America* 146:2753.
- Lents CE, Hardin LW. 2019. Fuel burn and energy consumption reductions of a single-aisle class parallel hybrid propulsion system. *AIAA Propulsion and Energy Forum*, Aug 19–22, Indianapolis.
- Spakovszky ZS. 2019. Advanced low-noise aircraft configurations and their assessment: Past, present, and future. *CEAS Aeronautical Journal* 10:137–57.
- TRB [Transportation Research Board]. 2019. Factsheet: Sustainable alternative jet fuels and emissions reduction. Online at http://onlinepubs.trb.org/onlinepubs/acrp/acrp_wod_41Factsheet.pdf.
- Uranga A, Drela M, Greitzer EM, Hall DK, Titchener NA, Lieu MK, Siu NM, Casses C, Huang AC, Gatlin GM, Hannon JA. 2017. Boundary layer ingestion benefit of the D8 transport aircraft. *AIAA Journal* 55(11):3693–708.
- Yutko BM, Hansman RJ. 2011. Approaches to representing aircraft fuel efficiency performance for the purpose of a commercial aircraft certification standard. MIT International Center for Air Transportation Rpt. No. ICAT-2011-05.

Advances are needed in battery technology and certification to enable hybrid electric aircraft.

Hybrid Electric Aircraft to Improve Environmental Impacts of General Aviation



Jean Botti is founder and chief executive officer of VoltAero.

Jean J. Botti

According to two recent reports (ATAG 2018; IHLG 2019), the aviation sector represents a major economic factor for the global economy: its economic value is estimated at \$2.7 trillion and it generates 65.5 million jobs. In 2018 airlines carried more than 4.3 billion passengers on scheduled flights, an increase of 6.4 percent from 2017; the number of departures grew from 36.7 million to approximately 38 million, an increase of 3.5 percent; and traffic in revenue passenger per kilometer expanded by 4.1 percent. International air traffic is expected to continue increasing, with average growth forecasts for the next 20 years of 4.1 percent per year.

With this growth and traffic, aviation is now responsible for 2 percent of global carbon dioxide emissions. Increasing concerns about global warming are pushing airlines and manufacturers to design new solutions to reduce pollution. Over the past 50 years, aircraft fuel consumption (and therefore CO₂ emissions) has been reduced by almost 80 percent per tonne-kilometer and noise at source by 20 dB.

To reduce aviation's environmental impact, the European Commission (2011) established the following objectives for aviation to reach by 2050:

- 75 percent reduction in CO₂ emissions per passenger per kilometer,
- 90 percent reduction in NO_x emissions,

- elimination of emissions during aircraft taxiing, and
- use of alternative fuels with improved environmental performance.

These commitments require efforts on several fronts, including research on technologies and operations and the development and adoption of new energy sources (e.g., biofuel, electric).

Customer requirements must also be met:

- Safety through complete redundancy on the kinematic chain (electrical, mechanical, or hybrid);
- Reduction of noise pollution and emissions, especially around airports; and
- Savings in energy and operating costs.

A New Era of Propulsion Systems: Hybrid Electrification

Noise Reduction

The reduction of noise pollution associated with aviation is essential, particularly for pilot training, which is a significant potential source of noise pollution given frequent rotations (takeoffs and landings). Commercial traffic is a major noise source, but general aviation noise must also be addressed. In France, for example, certain general aviation airports around Paris, like Toussus-le-Noble (about 25 km southwest of the city), close on Sundays to limit noise disturbances; only planes equipped with silencers are permitted to fly.

*The relative simplicity of
an electric motor may
support reduced maintenance
and a significantly longer
service life than
the thermal engine.*

Aircraft noise comes from multiple sources (e.g., the fan, the airframe), and the use of electric power reduces some noise more than others. Hybrid electric aircraft will allow quieter operation while maintaining the capacity to cover desired flight distances:

- On the ground and during takeoff, the use of electric traction in the wheels (etaxiing) reduces fuel consumption and eliminates noise.
- On initial climb, in flight, and during landing, electric motors are quieter than an internal combustion engine.

Lower Costs

The cost of operating an aircraft depends on many parameters, including

- consumption and type of energy used (e.g., aviation gas [avgas], unleaded automotive gasoline for traditional piston engines, Jet-A1 [kerosene] for turbines and diesel engines, electricity);
- maintenance (parts, labor) and service;
- hangar, landing, and parking fees;
- insurance (depending on the pilot's experience and coverage guarantees); and
- other items such as personnel costs and air traffic control fees.

For controlling recurrent costs, electricity brings undeniable advantages. In France, for example, the cost of electricity is €0.13/kWh, which is less than the cost of avgas (€0.21/kWh) (these rates are roughly comparable throughout Europe).

Here is an example to illustrate the difference in cost: A Cessna 172 consumes 10 gallons/hour of avgas at 110 knots, or 19 liters/100 km. At a cost of €1.83/liter, the total cost is €35/100 km (the energy in the 19 liters of avgas is 204 kWh).

In France 20 kWh of electricity at the grid is €2.6 (€0.13/kWh), so for an equivalent 204 kWh the total cost would be €26.52/100 km. There is thus a 24 percent saving with electricity over avgas. Once the infrastructure is in place, most general aviation aircraft will recharge at the grid in the hangar.

Intelligent management of an aircraft's electrical network can optimize energy consumption, with a more precise allocation of resources and parasitic loss reduction. This makes it possible to substantially reduce the energy needs of the main and auxiliary networks.

Furthermore, the relative simplicity of an electric motor makes it possible to envision reduced maintenance and a significantly longer service life than current configurations that use the thermal engine as the main propulsion element.

Overall, hybrid electric aircraft will

- prompt the development of new products and services for general aviation,
- stimulate and guide the establishment of a competitive industry in energy storage technologies for aircraft propulsion (whether electric or hybrid) and system management,
- spur technologies to advance for adaptation to ever larger aircraft,
- support intensive aviation training—by reducing noise at small airports where novice pilots train—to meet the growing need for pilots generated by continued increases in air traffic, and
- enhance the ability to meet environmental regulations.

The State of the Art

The design and manufacture of commercial aircraft with hybrid or electric propulsion require the development of technologies and skills to test concepts and select the best technical choices.

In recent years, multiple projects for the development of all-electric light aircraft have been launched, but many were private initiatives with relatively limited industrial prospects. The first demonstrations were developed by the Airbus Group (the personnel involved now work at VoltAero):

- The electric Cri-Cri (presented at the 2011 Paris Air Show) is a 180 kg single-seat piloted airplane equipped with a standard electric motor and batteries for a flight duration of 25 minutes. The aircraft was utilized as a flying testbed and performance laboratory, allowing R&D teams to acquire experience in battery integration, energy management, energy recovery, and the variable pitch of the propellers.
- The experimental prototype E-Fan was presented at the 2013 Paris Air Show and completed a historic English Channel crossing on electric power in 2016. The two-seater plane, designed to provide tangible proof of the concept's effectiveness, was made entirely of carbon composite material, 6.67 meters in length, with a wingspan of 9.5 m and a weight of 650 kg. It had a range of 48 minutes and the propulsion was provided by two electric motors with a maximum combined power of 60 kW, driving two ducted propellers (eight blades) of fixed pitch.

Today, there are more than 200 electric aircraft projects worldwide and the aviation electrification market is expected to be valued at \$4–\$5 billion over the next decade. Table 1 shows just a few projects for electric or hybrid electric aircraft under development.

The domain of electric/hybrid aircraft remains in an emerging phase. The major challenge is that the range and certification standards have yet to be defined, as no all-electric aircraft have been certified, because of a lack of sufficient technological capacity. However, hybridization can significantly reduce operational risks with the redundancy brought by an internal combustion engine.

In this context, VoltAero is working to develop Cassio, a family of 4- to 10-seat modular electric hybrid aircraft intended for initial pilot training as well as the general aviation sector (figure 1; UBS Investment Bank 2019). Using an existing airframe for its flight testbed, VoltAero's baseline design retains the original aircraft's "push-pull" propulsion system, and because the airframe is already completely certified, the company can focus on development of the hybrid propulsion system.

No all-electric aircraft have been certified, because of a lack of sufficient technological capacity.

The Cassio hybrid propulsion system is composed of two electric motors located on the wings, powered by battery packs (in each wing) that deliver an output of 60 kWh each. The combustion engine is in the aft fuselage, delivering 300 kW, combined with an electric motor of 180 kW in a hybrid power module, for a total output of 600 kWh, as the propulsion is distributed between the wing-mounted motors and the aft-fuselage hybrid power module. Through the energy it produces, the power module's combustion engine also recharges the batteries during flight (which would not be possible with a fully electric system), offering 3.5 hours of flight autonomy (with the possibility of extending to 5 hours).

With this propulsion configuration, the aircraft can taxi and take off on full electric energy while the combustion engine remains in idle mode, ready to take over in case of failure or to contribute when the cruise

TABLE 1 Electric/hybrid aircraft projects in progress

| | Eviation | Zunum | Ampaire | Diamond Hybrid |
|------------------------------|---|---|--|---|
| Projects | Alice Commuter  | ZA10  | TailWind  | DA40 hybrid electric  |
| 1st flight | TBD | TBD | TBD | Oct 31, 2018 |
| Usage (range) | Regional transportation (RA: 650 miles) | Regional transportation (RA: 700 miles) | Regional transportation (RA: 560 km) | Electric config.: 30 min Hybrid config.: 5 h |
| Number of pax | 9 | 12 | 9 (demonstrator: 6) | 2 (demonstrator) |
| MTOW | 6,350 kg | 5,200 kg | Demonstrator: 2,100 kg | - |
| Energy power | Li-ion 900 kWh 3 x 260 kW | 1 MW | Demonstrator based on a Cessna Skymaster | Battery: 2 x 12 kWh Thermal: 110 kW Electric: 2 x 75 kW |
| Certification | No hybrid or electric aircraft certified to date | | | |

MTOW = maximum takeoff weight; pax = passengers; RA = range.



FIGURE 1 Graphical rendering of the VoltAero Cassio hybrid electric aircraft.

phase starts. Landing also will be fully electric. The battery discharge at takeoff is estimated at 20 percent; the discharge limit should be 50 percent (e.g., during the cruise phase). The discharge/recharge cycles occur at 50–85 percent so that the battery is preserved during the cruise phase.

The electric/thermal hybrid aircraft will achieve substantial energy savings while in cruise and demonstrate excellent performance during the flight cycle. Maintenance costs may be reduced because electric motors

are more reliable than internal combustion engines and require little maintenance.¹

For commercial use (based on the range required) the Cassio aircraft could be configured in three modular concepts:

- pure electric (range of less than 200 km)
- mild hybrid (range of 200–600 km)
- heavy hybrid (range greater than 600 km).

Fuel economy and CO₂ reduction will vary based on these configurations.

Technological Challenge: Batteries

Energy Density

Batteries are a key technology for hybrid and electric propulsion, but they will have to reach a level of energy

¹ This can be explained as follows: The thermal engine in this context is used as a range extender and as such always functions at its best operating point, which greatly extends its life compared to a conventional propulsion thermal engine. Lithium-ion batteries involve very little maintenance: when they are dead they are simply replaced.

density of around 350 Wh/kg at the level of the entire battery pack within the next 5 years. New batteries are being studied to improve energy density in order to reduce weight.

Today, automotive batteries reach energy densities on the order of 100 Wh/kg (at pack level), and approximately 30–50 Wh/kg for commercial aviation (as a supplementary power source). These differences result from certification and qualification constraints. As explained in the next section, aviation must be very conservative in its qualification of batteries, so the safety margins for battery charging and discharge are very stringent. Reaching 350 Wh/kg is thus a real technological challenge.

Battery Charging

The standard charging system for batteries in current prototypes requires approximately 3–4 hours for a full charge.

In the case of hybrid aircraft, the industry needs to create a charging system that is adapted to the specific characteristics of the batteries that will be developed and that can be used for recharging during flight.

Currently, there is no adequate electrical infrastructure at airports for charging batteries. The definition and implementation of a dedicated system is of strategic importance. Connectivity to the network, aircraft access to the charging terminal, the safety and ease of the procedure, the billing system...all are subjects that require study and development.

Two challenges to be solved concern the heating and cooling of batteries and preservation of their durability and safety over time. This is why recharging methods (strategies, management, and controls) will need to be adapted to both the uses (e.g., frequency and charging time) and the technical specifications of the batteries (e.g., power, optimal recharging time, aging).

Operational Safety and Prediction of Remaining Charge

Beyond the energy density constraint, the development of lithium-ion/lithium-polymer batteries for aviation applications—for propulsion in particular—presents two major obstacles:

1. Achievement of a level of operational safety that allows the battery to be certified
Improvements in safety and reliability are paramount. Overheating of the battery pack would put the aircraft at risk and therefore cannot be tolerated. For aero-

nautical applications, the most feared event is a fire. Standards require that no flames or smoke emerge from the battery pack inside the aircraft. (In comparison, for an automobile, standards under development will require the prevention of flame or smoke for 5 minutes in the passenger compartment only, to give passengers time to get out.)

Thales/Boeing certified the 787 Dreamliner's lithium-ion batteries, but then experienced several fires during the aircraft's operation, including a "thermal runaway." This led to a design review and the decision to provide both better protection around the battery and a means to evacuate gases from the aircraft. These measures increased the airplane's drag, thus countering the interest in switching to lithium-ion batteries in the first place. SAFT/Airbus was unable to certify the A350 XWB's lithium-ion battery and had to revert to nickel-cadmium technology. In a lightweight aircraft, Siemens had a battery fire that killed two people, which led to discontinuation of the project.

Standards require that no flames or smoke emerge from the battery pack inside the aircraft.

2. Ability to predict remaining energy in the battery pack with acceptable accuracy

Current lithium-ion battery systems have a state-of-charge indicator. The accuracy of these indicators is generally acceptable at the start of life under standard conditions of use (5–7 percent for smartphone applications, 3–5 percent for automotive applications). However, under extreme conditions of use (for example, in extreme cold or during high power demands), the accuracy of this indicator (as well as the actual power output) can be greatly degraded. Reduced accuracy also can occur at the end of the battery's life. For an aeronautical propulsion application, estimating the battery's state of charge is a critical function.

Coordination of Other Parameters

Other important parameters for batteries are safety, fast rechargeability by the internal combustion engine, lifespan (approximately 2,500 cycles), volume, and price.

Implementation of innovative battery technology will require coordinated efforts involving the aircraft, its electronics, the battery packaging, and integration into the aircraft (taking into account weight/volume constraints and maintenance challenges). The following steps will help guide efforts:

- Define an optimized electrochemistry based on ideal trade-offs among safety, energy, lifetime, and price.
- Define the most generic battery cell format possible.
- Guarantee good “processability” and the potential for industrial manufacturing.
- Make the best choices in terms of electronic architecture (e.g., redundancy, controls).
- Integrate all the components of the aircraft’s electrical system (e.g., propulsion systems, control systems, instrument panel) while respecting certification standards.
- Choose the best cooling solution (e.g., heat sink, oil or air cooling, two-phase).
- Define and optimize the mechanical installation and conditioning of the battery for weight reduction while meeting aeronautical standards (e.g., choice of materials, partitions, connectors; management of mechanical safety, fasteners, and shock and vibration constraints; accessibility for maintenance).
- Ensure redundancy by creating modules that will cross-feed the engines, which will avoid handling problems for the aircraft if one or more of the engines fails.

A New Way Forward for Pilots

For pilots, the introduction of hybrid electric propulsion will modify the management of energy in flight and the type of information to be processed. It will therefore be necessary to rethink the presentation of informa-

tion (the amount and nature) and the decision-making mode linked to energy management. These changes in flight management will impact certain aspects of pilot training. This area should be investigated, along with flight safety and program compliance for obtaining pilot licenses. Cockpits will need to be more “intelligent” and provide the right level of information to the pilot for power management.

Conclusion

The environmental impact of aviation is a major concern in terms of both emissions and noise. Some people are even seeking to reduce their reliance on air transportation.

Hybrid and electric propulsion for aircraft is an option to reduce both emission and noise levels. However, various challenges must be resolved to enable the introduction of electric aircraft capable of transporting hundreds of people. For example, the energy density of batteries is too low to allow the development of an all-electric aircraft with a decent range. And improving the safety and reliability of electric drive chains is essential for aircraft to be certifiable.

Despite these challenges, several companies around the world are pursuing efforts to develop technologies applicable in the aeronautical field, particularly for general aviation. This process can be considered “revolution by evolution.”

References

- ATAG [Air Transport Action Group]. 2018. Aviation: Benefits Beyond Borders. Geneva.
- European Commission. 2011. Flightpath 2050: Europe’s Vision for Aviation. Luxembourg.
- IHLG [Industry High Level Group]. 2019. Aviation Benefits Report. Montreal.
- UBS Investment Bank. 2019. Green power: Will climate change propel the sector towards hybrid electric aviation by 2028? New York.

The potential benefit of electrified aircraft propulsion is the flexibility it brings to the aircraft design space.

Electrified Aircraft Propulsion



John Langford



David Hall

John S. Langford and
David K. Hall

The past decade has seen the number of electric and hybrid electric cars sold increase from about zero to over 2 million per year at an annualized growth rate of over 60 percent (Hertzke et al. 2019). Is a similar revolution in store for aircraft? The rise of the *flygskam* (flight shaming) movement has created societal pressure to reduce flights that produce carbon emissions and raised both popular and regulatory interest in electric propulsion for aircraft.

This article reviews the prospects for widespread use of electrified aircraft propulsion (EAP) and concludes that a large-scale conversion as is currently seen in terrestrial use is unlikely in aviation. EAP is not a “drop-in” technology that can be easily retrofitted into existing designs. Indeed, its fundamental benefit is that it adds new dimensions to the aircraft design space. By blurring the lines between airframe and propulsion systems, EAP allows highly integrated designs that can be tailored to specific missions and performance objectives, and these designs are unlikely to resemble current aircraft.

Case Study: Electric Retrofit of a Commuter-Class Aircraft

Figure 1 shows what happens when a conventional commuter-class passenger aircraft is converted to operate on batteries. The results, based on a

John Langford (NAE) was founder and CEO and David Hall leads the Propulsion Group, both at Aurora Flight Sciences.

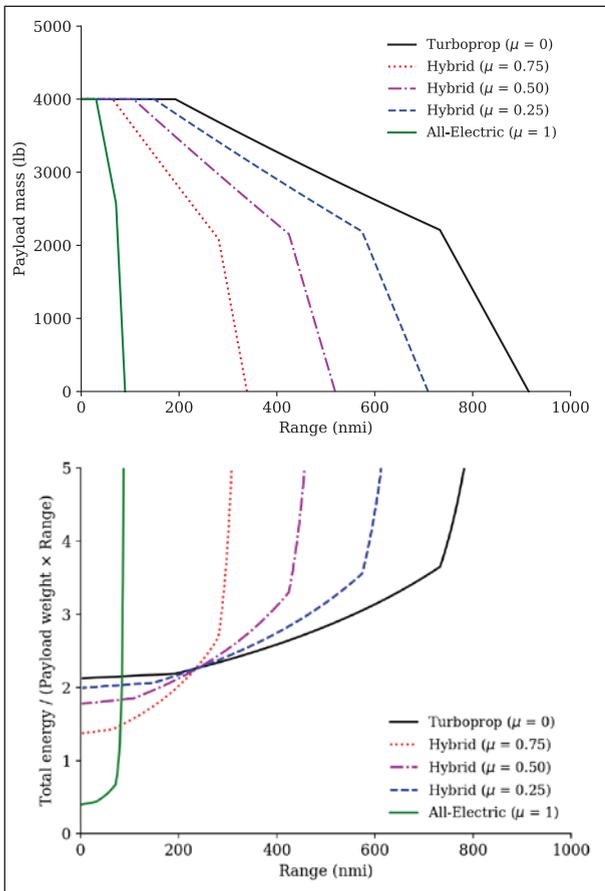


FIGURE 1 Payload-range capability (top) and total energy consumption (bottom) of a 19-passenger commuter-class transport aircraft with varying levels of hybridization. Battery-specific energy = 250 W-hr/kg; μ = (battery weight) / (total battery + fuel weight). nmi = nautical mile.

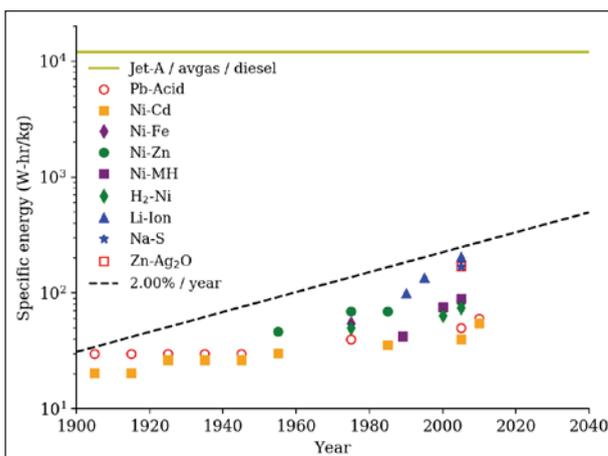


FIGURE 2 Historical trend in state-of-the-art battery cell energy density, compared to energy densities of hydrocarbon fuels, 1900–2040 (projected). Data from Zu and Li (2011).

de Havilland Canada DHC-6 Twin Otter, are broadly applicable to this class of turboprop-powered aircraft (e.g., PC-12, Caravan, Q-400, ATR-72). Propeller power is generated by a combination of fuel-burning gas turbines and battery-powered motors. The degree of hybridization, μ , is the weight of the battery divided by the combined battery + fuel weight. When $\mu = 0$ the aircraft is a conventional turboprop, and when $\mu = 1$ the aircraft is entirely electric.

In the context of payload and range capability, electrification always makes the performance worse. This is because the energy density in current batteries, no better than 250 W-hr/kg (watt-hour per kilogram), is a small fraction of that for liquid hydrocarbon fuels (figure 2). Major increases in battery energy density—for example, a doubling to 500 W-hr/kg—improve the results but do not change the fundamental trend of reduced range capability relative to energy-dense hydrocarbon fuel.

The situation improves if one considers energy efficiency, as in the lower graph in figure 1, showing the ratio of total energy required to the product of range and payload weight, a measure of energy usage normalized for every mission. Battery-electric propulsion can achieve only a fraction of the range of the baseline turboprop, but it is considerably more efficient at those ranges. The achievable range can be increased with the decreasing μ , but energy efficiency decreases.

The fundamental trade is between the power-conversion efficiency of an electric system, which can be a factor of 2 higher than for a gas turbine engine, and the energy density of hydrocarbon fuel, which is an order of magnitude higher than for batteries. The implication is that, for very short ranges, electric propulsion *might* have an energy efficiency advantage.

Energy efficiency is also an excellent proxy for CO₂ emissions, which basically scale with the mass of fuel burned. For a battery aircraft, emissions come from the power grid rather than the onboard turbine, and hence the source of power for the grid matters. Emissions in the Northwestern United States, where the grid has a high fraction of hydro power, are lower than in the Midwest, where grid power comes mostly from coal-fired generators.

Energy efficiency is not the sole determinant of aircraft operating costs. Direct operating costs (referred to as cash aircraft-related operating costs, or CAROC) are measured in dollars per available seat mile and include fuel, maintenance, crews, insurance, and airport fees. Direct operating costs account for between

one-third and two-thirds of aircraft-related operating costs (AROC), which include costs related to acquiring and owning or leasing the aircraft. These vary with the acquisition cost of the aircraft and its use; commercial airlines use their assets many more hours per year than corporate, charter, or private operations.

It is generally accepted that to successfully launch a new aircraft type, the CAROC must be at least 15 percent below that of the aircraft it is replacing. Since fuel is typically 10–20 percent of AROC, figure 1 suggests that this will be possible for EAP only at extremely short ranges; hence the interest in trainers or electric vertical takeoff and landing (eVTOL) air taxis with short ranges.

All-Electric Aircraft

Urban Air Mobility

The potential efficiency and cost benefits of electric propulsion at short range have led to a rapid rise in interest and investment in eVTOL for urban air mobility (UAM). For example, the ride-hailing company Uber has developed plans to fly riders to their destination via eVTOL. Building on NASA research, the company envisions four-passenger vehicles with a range of 60 miles, cruise speeds of at least 150 miles per hour, and a battery-electric propulsion architecture (Uber 2016). The latter not only speaks to the CAROC benefits but also aims to address issues of carbon footprint, local emissions, and noise.

To address the UAM market, Aurora Flight Sciences developed a passenger air vehicle (PAV) prototype (figure 3) to demonstrate the feasibility of an electric propulsion system and autonomous operations. The PAV is a separate-lift-and-cruise configuration: vertical takeoff and landing are achieved with multiple lift rotors, which are then shut off for efficient, wing-borne, propeller-driven forward flight in cruise. This design allows for VTOL operations in an urban environment while maximizing range with a battery energy storage system. The feasibility of UAM missions depends not only on electric propulsion technologies but also on novel vehicle configurations like the PAV to meet challenging new efficiency, emissions, and community noise requirements.

Commercial Aircraft

At present, it appears that EAP makes economic sense only for aircraft that fly extremely short ranges (50–200 miles), such as general aviation aircraft, especially train-



FIGURE 3 First flight of the Aurora Flight Sciences passenger air vehicle, January 22, 2019. Photo credit: Aurora Flight Sciences.

ing aircraft, and eVTOL air taxis. Is there any potential for large aircraft?

For commercial transports, the large amount of energy required to move hundreds of passengers hundreds or thousands of miles poses a challenge for battery energy storage. The difference in energy density between batteries and hydrocarbon fuels means the range of an all-electric transport will be significantly reduced relative to an equivalent gas-burning aircraft, as in figure 1 for smaller aircraft. The high efficiency of current large engines—in many cases emitting less CO₂ per unit power produced than the grid from which the competing batteries would be charged—further complicates the value proposition of an all-electric airliner (Epstein and O’Flarity 2019).

The technical challenge of battery-powered transports is illustrated in figure 4, which shows contours of the battery-specific energy (BSE) required to enable an all-electric aircraft with a given payload fraction—the ratio of payload weight to aircraft maximum takeoff weight—and range. Data points for the payload and range capability of existing aircraft are included.

Even with generous assumptions about aerodynamic and propulsive efficiency, structural weight, and required reserves, a specific energy over 300 W-hr/kg is required to enable the capability of the 19-passenger DHC-6-400 Twin Otter. Taking into account that this value of BSE includes extra weight of packaging and thermal and safety protections, which can discount the cell-level performance shown in figure 2 by up to half, it becomes clear that battery-powered transports are more than 20 or 30 years away without breakthroughs in battery technology inconsistent with the historical trend.

Hybrid Electric Aircraft

Rather than attempting to displace aircraft fuel with batteries, there has been growing interest in hybrid

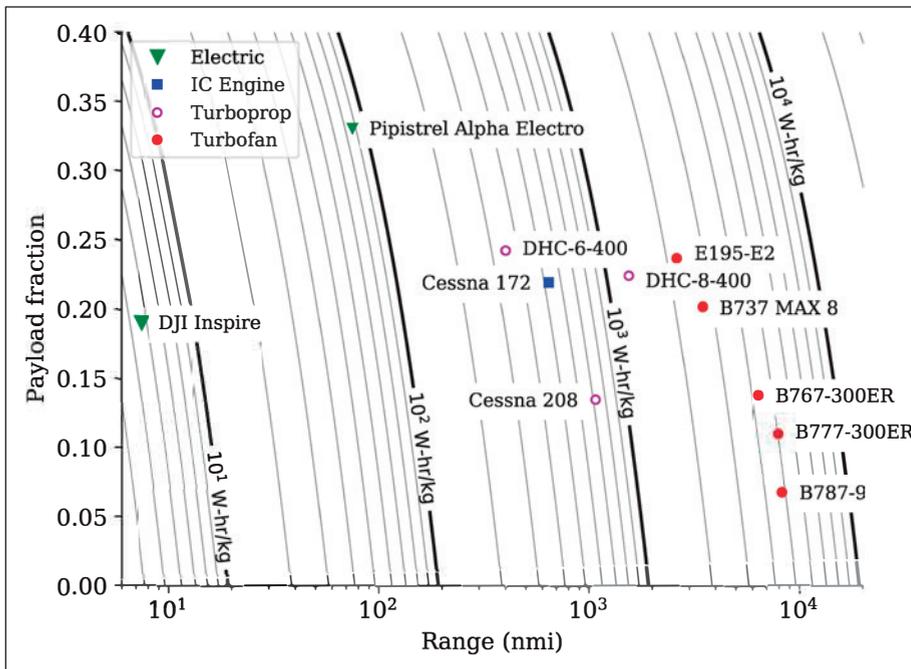


FIGURE 4 Required battery-specific energy for a given payload fraction and range. Assumptions: lift-to-drag ratio = 20, propulsion system efficiency = 0.8, empty weight fraction = 0.4, no reserves. Payload-range capabilities of existing aircraft plotted for comparison. IC = internal combustion; nmi = nautical mile.

electric concepts, i.e., propulsion systems that can draw from energy stored both in batteries and in hydrocarbon fuel. Hybrid electric vehicles in the automotive industry enabled step-change improvements in fuel efficiency and paved the way for the current generation of all-electric vehicles. Could the same model apply to electrified aviation?

In answering this question, it is important to point out the differences between automobile and aircraft propulsion. First, terrestrial vehicle energy requirements are much less sensitive to weight than aircraft. Second, and perhaps more important, hybrid and all-electric cars enjoy energy savings due to regenerative braking. For aircraft, there is little opportunity for analogous regenerative deceleration: the energy recovery potential of an aircraft cruising at high altitude is much smaller than the energy used to overcome irreversible drag over the course of a commercial transport mission. Further, aircraft already practice regeneration without an electric system: during descent, the engine power is reduced and the glide slope extends the range by using the aircraft potential energy to generate extra thrust.

Strategies for hybrid electric aircraft are thus centered on improving gas turbine performance through integra-

tion of a supplemental electrical power source. Gas turbines have long been preferred for transport aircraft propulsion because of their high efficiency, power-to-weight ratio, high-altitude capability, and low emissions. One drawback is that they are most efficient at their highest power, and designing the engine to meet peak power requirements during climb reduces the maximum achievable efficiency during cruise. Hybrid electric systems have the potential to remove this physical constraint by augmenting the power of the turbine during high-power conditions, enabling the engine to be optimized for peak performance during cruise, where most of the fuel is burned, at the cost of a minimal battery

electric system. The inclusion of a high-power electric system for propulsion also opens up possibilities for new technologies like electric taxiing and vehicle system-level energy management, based on close integration between propulsion and aircraft electrical systems.

A recent study by United Technologies suggests that such a hybrid system for a future single-aisle transport could reduce fuel burn by 4.2 percent and energy consumption by 0.3 percent relative to an advanced-technology turboprop (Lents and Hardin 2019). Another claims a hybrid reengine of a regional turboprop could reduce cruise fuel consumption by 25 percent, albeit at reduced range (Bertrand et al. 2019). The difference in results highlights the importance of both mission (electrification may have a greater benefit at short range) and the baseline for comparison; when considering new aircraft designs, one must be careful to compare equivalent levels of technology and equivalent mission requirements between electrified and conventionally powered aircraft.

Distributed Electric Propulsion

Discussion to this point has focused on EAP concepts with some level of battery energy storage. Another

potential benefit of electrification, independent of energy storage medium, is the decoupling of mechanical power generation and thrust generation processes. Doing so would continue a decades-long trend in aircraft engine design: the shift from turbojets to turbofans improved efficiency by using a larger mass of lower-velocity bypass flow to generate thrust, and the recent introduction of geared turbofans relaxed the speed constraint on the fan and turbine, allowing both to be designed at their most efficient speeds.

The concept of distributed electric propulsion (DEP) takes this decoupling one step further, by introducing flexibility in the number and arrangements of propulsors (propellers or fans). This benefits the propulsors, which follow a cube-squared scaling: the weight of a propulsor is approximately proportional to its diameter cubed and, for fixed jet velocity, the thrust is approximately proportional to the diameter squared. A distributed system with many propulsors will thus weigh less than a single propulsor producing the same thrust at the same jet velocity.

Alternatively, distributed propulsors provide for a larger total fan area and thus lower jet velocity and higher efficiency than a single propulsor with the same total weight, although in this case the benefit also trades against an increase in nacelle drag, which scales with fan area. Electrification allows distributed propulsors to be driven by a single gas turbine core, which, experience has shown, will be more efficient than multiple smaller cores providing the same net power (Lord et al. 2015). These benefits must be traded against the added weight, transmission losses, and complexity of an electric power distribution system, which have to be evaluated at the overall vehicle performance level.

A Turboelectric VTOL Model

A notable recent example of a DEP design is the DARPA XV-24A concept developed by Aurora Flight Sciences. The novel tilt-wing/tilt-canard vehicle configuration (figure 5) arose in response to challenging requirements for efficient vertical lift capability and high-speed cruise at 400 knots, which are not achievable with conventional rotorcraft or tilt-rotor designs. DEP was a key enabling technology that allowed large propulsor disk area for efficient vertical takeoff without a large-diameter rotor and associated aerodynamic disadvantage at high speed.

The envisioned propulsion system had a turboelectric powerplant: electrical power for motor-driven fans was



FIGURE 5 DARPA/Aurora Flight Sciences XV-24A LightningStrike concept for a distributed electric propulsion design. Image credit: Aurora Flight Sciences.

developed by electric generators coupled to a gas turbine engine with no batteries. This architecture leverages the configuration benefits of DEP while achieving the payload and range potential with energy-dense hydrocarbon fuel. The concept was revolutionary, but it was unable to achieve the needed full power capability because of component limitations and was cancelled by DARPA before it could demonstrate the benefits of DEP at full scale.

Approaches to Propulsion-Airframe Integration

Beyond improving the efficiency or weight of the propulsion system, DEP opens up potential benefits in overall vehicle performance through propulsion-airframe integration. Rather than designing the engine as an isolated, thrust-producing system, integrated design of the combined propulsion-aircraft system may unlock aerodynamic efficiency improvements for both, because DEP provides the designer with the flexibility to distribute and integrate propulsors in the vehicle to an extent not possible with conventional propulsion.

Boundary Layer Ingestion

One such strategy is propulsion with boundary layer ingestion (BLI). The basic principle of BLI is for the engine to produce thrust by ingesting and accelerating air in the so-called boundary layer near the surface of the vehicle. Friction reduces the velocity of this flow in the frame of reference of the vehicle, which means the same thrust can be produced using less power.



FIGURE 6 NASA aircraft concepts using distributed electric propulsion (DEP). The STARC-ABL (top) and N3-X (middle) concepts use distributed turboelectric propulsion to enable boundary layer ingestion (BLI), and the X-57 Maxwell (bottom) uses motor-driven propellers for blown lift.

Wind tunnel experiments carried out by MIT, Aurora Flight Sciences, and Pratt & Whitney at the NASA Langley Research Center showed a power savings of 10 percent by ingesting approximately 17 percent of the

boundary layer of an advanced twin BLI-engine vehicle concept (Uranga et al. 2017). Analysis shows that the benefit increases with the amount of boundary layer ingested, and DEP provides a means to do this.

Figure 6 shows two NASA concepts with BLI enabled by DEP. One (top image) is a conventional tube-and-wing aircraft configuration with a turboelectric propulsion system and a motor-driven BLI fan at the back of the fuselage. The other (middle image) is a hybrid wing-body concept with distributed BLI propulsors ingesting a large fraction of the vehicle's upper surface boundary layer.

Blown Lift

Another DEP-enabled propulsion-airframe integration strategy is blown lift, which positions a wing and propulsor relative to each other such that the pressure field induced on the wing and the deflection of the propulsor jet increase the overall lift beyond that of the isolated airfoil.

The benefits of short landing and takeoff are well known and implemented in aircraft such as the DHC-6 Twin Otter, used in the hybrid payload-range analysis above, but these have been limited by the amount of blowing that can be achieved with only two or four propulsors. DEP opens the door for super-short takeoff and landing with smaller propulsors distributed along a larger segment of the wing's span, enabling short field performance that begins to make it competitive with more technically complex eVTOL concepts.

Alternatively, the blown wing benefit can enable typical field lengths with less wing area and higher wing aspect ratio, leading to improved aerodynamic efficiency during cruise. This is the idea behind the NASA X-57 Maxwell concept (bottom image in figure 6), which claims reduction in cruise energy consumption rate by a factor of 4.8 relative to an unmodified, conventionally powered aircraft (Borer et al. 2016).

Conclusion and Outlook

The potential benefit of electrified aircraft propulsion is the flexibility it brings to the aircraft design space. This benefit comes at the cost of components with increased weight and transmission inefficiencies, but there appear to be a variety of aircraft missions and vehicles that can leverage electrification in different ways. The conclusions drawn here do not differ materially from those of a 2016 consensus study of the National Academies of Sciences, Engineering, and Medicine, which reported

that battery-powered propulsion is well suited only to small vehicles with short range, and that distributed propulsion and boundary layer ingestion could yield significant performance benefits to commercial transport aircraft (NASEM 2016, pp. 51–70).

The potential for hybrid systems to improve the performance of gas turbine engines and propulsion-airframe integration effects such as blown lift also warrants further investigation. Other options for electrified propulsion, such as solar power or fuel cells, are beyond the scope of the discussion here, but they similarly offer benefits for unconventional vehicles or missions by introducing new options to the vehicle design space.

Challenges to implementing the vision for EAP remain. Urban air mobility may be feasible with current technology, but only just, and advances in the technology to improve the capability of UAM vehicles are necessary before transport-class hybrid concepts become competitive. Smaller concepts will require tens or hundreds of kilowatts, and larger transports could require a megawatt or more of electric power capability. Electric machines of these scales exist today for various ground-based applications, but new designs are needed to meet the stringent weight, efficiency, and reliability requirements for aviation.

All in all, there is reason to be cautiously optimistic about the future of EAP. The convergence of new technologies and new vehicles will allow new modes of mobility for the traveling public. The required innovations at the interface of aircraft, engine, and high-power electronics technologies will necessitate new interactions between established industries and generate opportunities for new entrants in an emerging industry. Finally, and not least, new technologies will inspire the next generation of students, researchers, scientists, and engineers in their drive to address the challenge of sustainability for aviation's second century.

References

- Bertrand P, Spierling T, Lents C. 2019. Parallel hybrid propulsion system for a regional turboprop: Conceptual design and benefits analysis. AIAA Propulsion and Energy Forum, Aug 19–22, Indianapolis: AIAA 2019-4466.c1.
- Borer NK, Patterson MD, Viken JK, Moore MD, Clarke S, Redifer ME, Christie RJ, Stoll AM, Dubois A, Bevirt J, and 3 others. 2016. Design and performance of the NASA SCEPTOR distributed electric propulsion flight demonstrator. 16th AIAA Aviation Technology, Integration, and Operations Conf, Jun 13–17, Washington: AIAA 2016-3920.
- Epstein AH, O'Flarity SM. 2019. Considerations for reducing aviation's CO₂ with aircraft electric propulsion. *Journal of Propulsion and Power* 35(3):572–82.
- Hertzke P, Müller N, Schaufuss P, Schenk S, Wu T. 2019. Expanding electric-vehicle adoption despite early growing pains. McKinsey & Company: Automotive & Assembly, August.
- Lents C, Hardin L. 2019. Fuel burn and energy consumption reductions of a single-aisle class parallel hybrid propulsion system. AIAA Propulsion and Energy Forum, Aug 19–22, Indianapolis: AIAA 2019-4396.
- Lord WK, Suci GL, Hassel KL, Chandler JM. 2015. Engine architecture for high efficiency at small core size. 53rd AIAA Aerospace Sciences Mtg, Jan 5–9, Kissimmee FL: AIAA 2015-0071.
- NASEM [National Academies of Sciences, Engineering, and Medicine]. 2016. Commercial Aircraft Propulsion and Energy Systems Research: Reducing Global Carbon Emissions. Washington: National Academies Press.
- Uber. 2016. Fast-forwarding to a future of on-demand urban air transportation. San Francisco: Uber Elevate.
- Uranga A, Drela M, Greitzer EM, Hall DK, Titchener NA, Lieu MK, Siu NM, Casses C, Huang AC, Gatlin GM, and 1 other. 2017. Boundary layer ingestion benefit of the D8 transport aircraft. *AIAA Journal* 55(11):3693–708.
- Zu C, Li H. 2011. Thermodynamic analysis on energy density of batteries. *Energy & Environmental Science* 4(8):2614–24.

The incorporation of sustainability in aircraft design may be precisely what enables the global acceptance and successful return of supersonic transportation.

Supersonic Flight and Sustainability: A New Horizon

Raymond Russell, Lourdes Maurice, and Rachel E. Devine



Raymond Russell



Lourdes Maurice



Rachel Devine

Nearly two decades ago the age of supersonic commercial aviation appeared to come to a close. The Anglo-French Concorde, which flew passengers at Mach 2 for 27 years, was retired in 2003.

Concorde was a technological marvel but plagued by high operating costs. The limited production run prevented carriers from achieving economies of scale, and Concorde failed to attain widespread commercial success. Factors such as increases in maintenance costs for the aging Concorde airframes, the fatal accident of July 2000 in France, and the slump in air travel after the terrorist attacks of September 11, 2001, all contributed to Concorde's relegation to the world's air museums (Learnmount and MacKenzie 2003).

Raymond Russell is head of sustainability, Lourdes Maurice is an independent consultant and advisor, and Rachel Devine is head of US policy, all at Boom Supersonic.

Several manufacturers are now working to ensure that the end of Concorde was not the end of the supersonic era. More than 50 years of technological progress enable quieter, more efficient supersonic aircraft. Indeed, current commercial aircraft are 80 percent more fuel efficient than the first jet airliners. According to the Aerospace Industries Association, a flight today produces 50 percent less CO₂ than the same flight in 1990 and aircraft noise footprints have shrunk up to 90 percent in the past 50 years.¹

The subsonic fleet's fuel efficiency and noise footprints have steadily improved, but the advances enabling these improvements—in computational design, propulsion systems, materials, route optimization, and others—have yet to be applied to a civil supersonic aircraft. Nonetheless, important progress is being made on supersonic applications, as reviewed in this article.

Rationale for Building Supersonic Commercial Aircraft

Despite the limited success of Concorde, the past decade has seen a rebirth of interest in commercial and business supersonic flight. New materials, advanced engines, and innovation in aerodynamics can render civil supersonic flight economically viable. Companies driven by the energy and enthusiasm of a new generation of engineers are building on the work of legacy manufacturers and the National Aeronautics and Space Administration (NASA) to bring back supersonic travel (e.g., figure 1).

From the first scheduled passenger flight in the United States in 1914 to today's transcontinental network, tourism, business, and the economy have thrived (Sharp 2018), and the tremendous benefits of aviation (IHLG 2017) will be compounded at higher speeds (ICAO 2019). Time is a valuable commodity in the 21st century, and supersonic aircraft will allow humans to travel farther in less time, making the world more accessible to new business connections, greater cross-cultural understanding, and stronger bonds between distant families.

What about Environmental Concerns?

The aviation sector produces about 2 percent of worldwide greenhouse gas emissions (CO₂) and accounts for 12 percent of all transportation-related emissions, although this share could grow as more people fly and



FIGURE 1 A proposed next-generation supersonic airliner: the 55-passenger, Mach 2.2 Boom Overture. Source: Boom.

other modes decarbonize² (Lee et al. 2010).³ These figures are small relative to other modes of transportation, but aviation is a high-profile target of the climate movement, especially as the rate of air travel is growing⁴—and outpacing the rate of improvement in aircraft fuel efficiency. Thus greenhouse gas emissions attributed to aviation are rising. But it is important to keep these figures in context: Passenger and cargo aircraft carry 35 percent of the value of world trade, transport more than 4 billion passengers per year, and support over 65 million jobs (IHLG 2017).⁵

Given society's increasing emphasis on environmental stewardship and concerns about the effect of air travel on climate change, can commercial supersonic

² Facts and figures, Air Transport Action Group, <https://www.atag.org/facts-figures.html>

³ We are aware of concerns about the effects of altitude emissions; this complex subject could not be accommodated within the length limits of this article. While many scientific uncertainties remain, it may be possible to avoid sensitive parts of the atmosphere while still realizing the benefits of commercial supersonic flight; for a discussion of advances and uncertainties, see IPCC (1999).

⁴ <https://www.atag.org/facts-figures.html>. This article was drafted before the devastating impacts of covid-19 on commercial aviation and around the globe. We believe the industry will recover but recognize that it will be some time before air travel service and growth return to 2019 levels.

⁵ <https://www.atag.org/facts-figures.html>

¹ AIA Environment, <https://www.aia-aerospace.org/issue/environment/>

flight become a reality in the 21st century? There are reasons to believe that sustainable supersonic flight is indeed viable—and in fact inevitable. In many ways, the focus of manufacturers on sustainability and reducing climate impacts may be the very thing that secures the return of supersonic transportation.

*Technological progress
can improve
supersonic aircraft noise,
fuel efficiency, and
carbon emissions.*

In this article we explore the environmental challenges and opportunities for commercial supersonic transport, focusing on noise and climate effects. The industry is leveraging technological progress to deliver improvements in supersonic aircraft community noise footprints, fuel efficiency, and carbon emissions, as well as operational changes and an international industry agreement to help mitigate environmental effects.

Community Noise

Successive generations of subsonic aircraft have become steadily quieter, thanks to continued improvements in propulsion technology as well as government-mandated phaseouts of noisier aircraft (FAA 2018). A key technological factor in this “quieting” of aviation is the move from turbojet engines to turbofan engines, and then from low-bypass turbofans to higher-bypass turbofans.

From Turbojet Engines to Turbofans

Concorde was an extraordinary technological achievement for its time. Its variable engine intakes and fly-by-wire system were industry firsts, and its Olympus 593 engines were the most thermodynamically efficient machines built to date (Leyman 1986).

But Concorde’s Olympus engines were noisy turbojets, and afterburners were used to produce the high thrust needed at takeoff and again to achieve supersonic speeds. Afterburners inject additional fuel into an engine’s jet exhaust downstream of the turbine, increasing jet noise. Fortunately, they are now unnecessary in this application.

Because airport noise is an important concern, and many people associate supersonic travel with Concorde’s disruptive airport noise, eliminating the need for afterburners is a critical prerequisite for widespread adoption of civil supersonic aviation. New supersonic aircraft designs are likely to employ low- to medium-bypass turbofans, rather than pure turbojets, substantially lessening noise impacts.

In a turbojet, air is compressed to a significantly higher pressure than the freestream. Fuel is then introduced and ignited, adding energy to the air. The flow loses a small amount of this energy to the following turbine stage. Finally, the flow exits the engine, producing thrust as a high-temperature, high-velocity stream of jet exhaust.

A turbofan’s engine core is essentially a turbojet, with a second thrust-producing pathway. The turbofan diverts a large amount of incoming air around the core, where a large fan slightly accelerates the flow to produce thrust. Because driving the fan requires relatively little energy from the turbine, a turbofan engine can produce much more thrust than a turbojet for the same fuel consumption.

The fast stream of air exiting the engine core is the dominant contributor to engine noise, and an ancillary benefit of relying more on bypass flow for thrust is a decrease in this jet velocity. Lighthill’s acoustic analogy relates the noise produced by a turbulent source to the eighth power of the velocity of that source (Goldstein 2003). As a result, subsonic engines have moved toward higher bypass ratios. Modern engines, such as the Airbus A320neo’s CFM LEAP⁶ or the forthcoming Boeing 777x’s GE9X,⁷ have bypass ratios of 11:1–12:1, meaning that 91–92 percent of air entering the engine flows around the core to be accelerated by the fan.

Noise Challenges for Supersonic Aircraft

Engineers continue to strive to build quieter engines. Those designing subsonic engines find that incentives to reduce both noise and fuel consumption are aligned by moving to larger-diameter, higher-bypass engines. However, this convenient parallel does not hold for supersonic applications. Supersonic engines will rely more on thrust from the jet core than do contemporary, high-bypass subsonic engines; figure 2 shows a compari-

⁶ <https://www.safran-aircraft-engines.com/commercial-engines/single-aisle-commercial-jets/leap/leap-1a>

⁷ <https://www.geaviation.com/commercial-engines/ge9x-commercial-aircraft-engine>

son of a subsonic and a notional supersonic engine. To further reduce noise, designers can leverage operational changes, discussed below.

As parts of an airframe begin to experience local supersonic flow, the corresponding shock waves add an additional term to the drag equation: wave drag, the cost of pushing a body faster than the speed of sound.

Drag considerations above Mach 1 require careful optimization of the cross-sectional area, necessitating lower-bypass engines to improve fuel efficiency at supersonic cruise. But that increase in fuel efficiency comes at the cost of noise performance near the ground, as the engine relies relatively more on thrust from the core's noisy jet exhaust. Supersonic aircraft thus require more thrust at takeoff and landing, where noise is a chief concern.

Despite these challenges, technology advances and new operational procedures ensure that the overall noise of new supersonic aircraft will not differ substantially from those of the existing subsonic fleet.

Operational Changes

Supersonic engines, sized for transonic acceleration and sustained supersonic cruise, have a greater margin of excess thrust at departure than subsonic aircraft and often use nearly all available thrust at takeoff. One proposed strategy to reduce supersonic aircraft noise during departure is programmed lapse rate (PLR), a computer-managed reduction in thrust after the takeoff roll.

Because of their excess thrust, supersonic aircraft should still be able to accelerate during the climb phase even after reducing power. PLR and accelerating climb-outs may offer significant benefits in noise reduction (Berton et al. 2017).

Another approach is to vary the wing's flaps and slats by computer (Berton et al. 2017), enabling the aircraft to operate closer to its best lift-to-drag ratio at all times. This action maximizes performance and removes the aircraft from the vicinity of communities more quickly.

Whatever technologies are employed, supersonic jets should aim to meet noise standards similar to those for subsonic aircraft,⁸ taking into account trade-offs with fuel efficiency (FAA 2017). The technology enabling this compliance exists or is within reach with additional research and technology development.

⁸ The most recent ICAO noise standard is Chapter 14, referred to as Stage 5 in the United States.

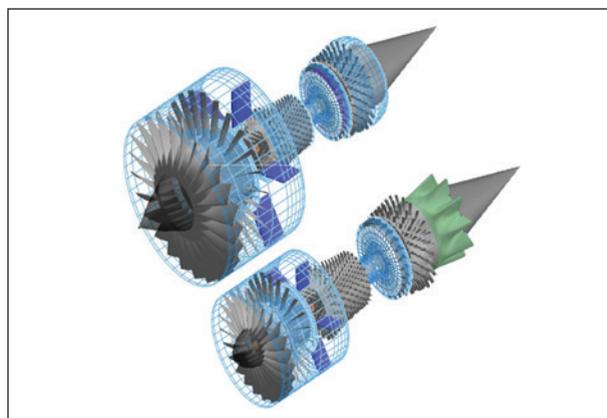


FIGURE 2 Comparison of the subsonic CFM-56 turbofan (top) and a notional derivative for potential civil supersonic aircraft applications (bottom). Note the substantially decreased fan size and differences in overall cross-sectional area. The supersonic derivative engine has also been modified with a lobed mixer nozzle (green) to enhance exhaust mixing and reduce noise. Source: NASA.

New Tools to Improve Supersonic Climate Impacts

Supersonic fuel efficiency has improved in part through aircraft-level improvements. In addition, sustainable aviation fuels and the potential to use offsets, facilitated by an international aviation industry agreement to offset and reduce carbon emissions, can help address the climate effects of supersonic flight.

Enhanced Fuel Efficiency

Fuel efficiency is as much a financial imperative for operators as it is a climate goal, as fuel outlays are a significant share of airline operating costs (IAG 2018).⁹ Manufacturers of supersonic aircraft today enjoy advances that were not available to Concorde's engineers.

Modern engines consume much less fuel per unit thrust than their predecessors. Over the past few decades subsonic aircraft have become on average roughly 1.5 percent more fuel efficient each year, and applying improvements in combustor and engine cycle design to new supersonic engines may correspondingly improve efficiency.¹⁰

⁹ For IAG Holdings (which include British Airways, Aer Lingus, and Iberia) fuel accounts for around 25 percent of total annual costs (IAG 2018).

¹⁰ <https://www.atag.org/facts-figures.html>

In addition, modern materials and manufacturing techniques allow for greater flexibility in shaping and weight reduction. Concepts such as area ruling (avoiding abrupt changes in cross-sectional area to manage wave drag and sonic boom) were understood in the 1960s, but engineers faced manufacturing limitations. For example, aluminum is difficult to form into curved, area-ruled shapes, so Concorde's aerodynamicists could not take full advantage of what they understood to be true at the time. Carbon composites, on the other hand, can be easily molded into the desired shape, so the next generation of civil supersonic aircraft will be much more area ruled, reducing drag at transonic and supersonic speeds.

Sustainable Aviation Fuels

While many other industries and modes of transportation are rapidly electrifying, long-haul air travel will likely rely on liquid hydrocarbons for years to come as jet fuel maintains a considerable energy-density advantage over the best available batteries. The industry must therefore try to reduce the net emissions of the fuel consumed during flight. Sustainable aviation fuels (SAFs) are a key solution and a growing—albeit still small—share of airline fuel use.

The best sustainable aviation fuels today offer up to an 80 percent reduction in lifecycle CO₂ emissions.

These fuels are considered “drop in,” conforming to the same specifications as Jet A. However, by employing renewable sources, SAFs can reduce emissions over the fuel lifecycle, accounting for emissions from production, transportation, and use. The best SAFs today offer up to an 80 percent reduction in lifecycle CO₂ emissions (Hileman et al. 2009).

While commercial use of SAF remains small, demand is rapidly increasing, and both government and industry are responding. Each year, more potential fuels are approved by regulators for use, more processing facilities come online, and more investment flows into the sector. An ASTM specification exists for qualification of new SAF projects; six “pathways” are approved for producing

SAF,¹¹ and ASTM is evaluating several more (ASTM International 2019).

This process has led to a number of interesting jet fuel sources. Fulcrum BioEnergy,¹² with investment from BP and United Airlines, uses municipal waste as a feedstock for fuel. LanzaTech,¹³ a partner of Virgin Atlantic, uses genetically modified bacteria to synthesize fuel from waste gases at steel, cement, and other industrial plants. Others, such as Carbon Engineering¹⁴ and Prometheus (Brustein 2019), turn directly to atmospheric carbon capture, recycling CO₂ from ambient air into hydrocarbon fuels. These novel methods add to the existing supply of more traditional biofuels, produced from corn, soy, forest residues, algae, and other sources.

Importantly, the industry is committed to ensuring that SAF substitution for fossil fuel will not result in other social ills: Demand for SAF crops will not incentivize adverse land-use changes (e.g., the conversion of virgin forests into cropland) or generate pressure on food crops, and production will not offset the environmental benefits of use.

SAF will be an important contributor to the environmental performance of supersonic aircraft. The incorporation of sustainability in aircraft design concepts may be precisely what enables the global acceptance and successful return of supersonic transportation. Manufacturers intend new aircraft to accommodate alternative fuels in much higher blends than currently possible or permitted. With greater market penetration, SAF should build a track record of safe operation and gain a reputation for safety that will allow the use of higher blends or pure SAF.¹⁵

Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)

Even when a flight operator uses SAF, some emissions remain. These must be offset to earn a license to fly. The International Civil Aviation Organization (ICAO) has undertaken CORSIA, a globally coordinated, market-based effort to mitigate aviation's climate impacts by requiring that growth in international

¹¹ The standards for the origin of an SAF require that it be chemically identical to conventional jet fuel and specify a maximum permitted blending ratio (50 percent) with conventional fuel.

¹² <http://fulcrum-bioenergy.com/>

¹³ <https://www.lanzatech.com/>

¹⁴ <https://carbonengineering.com/>

¹⁵ Commercial Aviation Alternative Fuels Initiative, www.caafi.org/focus_areas/deployment.html

aviation—supersonic or subsonic—be carbon neutral after 2020.¹⁶

Established in 2016, CORSIA is, in effect, a global climate accord for international air travel, and aviation was the first industry to have such a sectoral program. Because supersonic commercial service is most profitable on long-distance international routes, most of it will fall under CORSIA jurisdiction.

Any such offsetting program comes with challenging accounting questions, such as ensuring the quality of offset credits and avoiding double-counting of emission reductions (i.e., both in the generating country and under CORSIA). Proper implementation is critical to the program's effectiveness, and ICAO and its members have set up a centralized auditing process for CORSIA. The scheme can ultimately help ensure that commercial supersonic jets do not add to the carbon burden from commercial aviation.

Conclusion

The aircraft design process now includes environmental considerations alongside payload, range, and other familiar requirements. Challenges remain, but today's technology allows for widespread supersonic passenger travel in the near future. Global acceptance will be key for reintroduction, and will require that manufacturers be vigilant about addressing environmental concerns through design, production, and operation.

Building a new aircraft is an opportunity to improve the sustainability position of air travel, and it may be that very concern for the environment that will make supersonic air travel successful.

References

- ASTM International. 2019. ASTM D7566-19b: Standard specification for aviation turbine fuel containing synthesized hydrocarbons. West Conshohocken PA.
- Berton JJ, Jones SM, Seidel JA, Huff DL. 2017. Advanced noise abatement procedures for a supersonic business jet. *Aeronautical Journal* 122(1250):1–16.
- Brustein J. 2019. In Silicon Valley, the quest to make gasoline out of thin air. *Bloomberg*, Apr 30.
- FAA [Federal Aviation Administration]. 2017. Stage 5 airplane noise standards. *Federal Register* 82(191):46123.
- FAA. 2018. History of noise. Washington.
- Goldstein ME. 2003. A generalized acoustic analogy. *Journal of Fluid Mechanics* 488:315–33.
- Hileman JJ, Ortiz DS, Bartis JT, Wong HM, Donohoo PE, Weiss MA, Waitz IA. 2009. Near-Term Feasibility of Alternative Jet Fuels. Santa Monica: RAND Corporation.
- IAG [International Airlines Group]. 2018. 2018 Annual Report. Madrid.
- ICAO [International Civil Aviation Organization]. 2019. Environmental Report: Destination Green—The Next Chapter. Montreal.
- IHLG [Industry High Level Group]. 2017. Benefits of Aviation. Montreal.
- IPCC [Intergovernmental Panel on Climate Change]. 1999. Aviation and the Global Atmosphere, ed Penner JE, Lister DH, Griggs DJ, Dokken DJ, McFarland M. Cambridge UK: Cambridge University Press.
- Learmount D, MacKenzie C. 2003. High costs clip Concorde's wings. *FlightGlobal*, April 14.
- Lee DS, Pitari G, Grewe V, Gierens K, Penner JE, Petzold A, Prather MJ, Schumann U, Bais A, Bernsten T, and 3 others. 2010. Transport impacts on atmosphere and climate: Aviation. *Atmospheric Environment* 44(37):4678–734.
- Leyman CS. 1986. A review of technical development of Concorde. *Progress in Aerospace Sciences* 23(3):185–238.
- Sharp T. 2018. World's first commercial airline: The greatest moments in flight. *Space.com*, May 22.

¹⁶ <https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx>

Advanced quantitative risk assessment methods can provide near-term added value to the safety and economic performance of air travel.

Embracing the Risk Sciences to Enhance Air Travel Safety



John Garrick



Ali Mosleh

B. John Garrick and
Ali Mosleh

Increased dependence on autonomous systems is a significant driver for advocating more rigorous *proactive* risk analyses (Ramos et al. 2019) of the safety of air travel. Modern aircraft alert systems represent a target area for quantitative risk assessments (QRAs). Examples of such systems are the traffic alert and collision avoidance system (TCAS), wind shear warning system, enhanced ground proximity warning system, and maneuvering characteristics augmentation system (MCAS). This paper highlights the value added of applying rigorous and quantitative methods from the risk sciences to assess and enhance the safety and performance of air travel.¹ The scope is limited to methods of analysis and their value added.

Introduction

In industries such as nuclear power where QRA methods have matured over several decades, the methods have provided major economic benefits in decision making on plant design, operations, and maintenance (Garrick 2014).

¹ The value added of such analysis has been cited by the National Academies in several reports, including one on the Fukushima nuclear accident (NASEM 2014).

John Garrick (NAE) is distinguished adjunct professor at the B. John Garrick Institute for the Risk Sciences and Ali Mosleh (NAE) is distinguished professor and Evelyn Knight Chair in Engineering at the Henry Samueli School of Engineering and Applied Science, both at the University of California, Los Angeles.

In fact, the economic advantages of QRA became apparent very early (PLG et al. 1981, 1982), resulting in hundreds of millions of 1982 dollar savings to the plant owners by demonstrating regulatory compliance of safety without the major modifications recommended by intervenors.²

A second early example of QRA involved the Beznau nuclear plant in Switzerland. A QRA (PLG 1989) provided compelling evidence to the authorities that a two-train safety system could be reduced to a single train with little to no impact on risk. The savings to the plant owner were in excess of 100 million 1988 dollars.

To illustrate the application of QRA methods to enhance the safety of air travel we focus on the risks of TCAS failure and pilot error.

The QRA Framework and Methods of Analysis

Complex systems, whether natural or human designed, pose formidable predictability challenges in terms of understanding and quantifying risks. These challenges have two main dimensions: (1) complexity in terms of topological, functional, and behavioral features and (2) limitations in data and knowledge needed to understand the complexity.

In specific applications the focus is on identifying the scenarios³ that lead to extremely rare but highly significant system states (e.g., unanticipated catastrophic failures). Such scenarios are often at or outside the boundaries of scientific and engineering knowledge and also are easily masked by model abstractions and solution techniques.

Over the past several decades QRA (also known as probabilistic risk assessment, PRA; Garrick 2008) has offered a *proactive* way to think about and analyze the safety and performance of complex systems. The primary techniques include deductive and inductive logic models (e.g., event trees and fault trees) for modeling sequences of events (i.e., risk scenarios) and their contributing subevents.

The 1975 *Reactor Safety Study* (USNRC 1975) was the first large-scale application of such methods. It developed and used a combination of fault tree and

event tree modeling techniques to not only identify accident conditions and their consequences but also evaluate their probability and uncertainties in the probabilities. Analysis of scenarios individually and in the aggregate makes it possible to identify safety vulnerabilities, rank contributors to risk by importance, quantify uncertainties, and make risk-informed decisions.

QRA offers a proactive way to think about and analyze the safety and performance of complex systems.

QRA techniques have gone through many upgrades and been used to assess the safety of other complex industrial installations and systems such as chemical process plants (Spouge 1999), space missions (Stamatelatos and Dezfuli 2011), and civil aviation (Mosleh et al. 2007). The aerospace industry is employing QRA techniques selectively (Kuchar et al. 2004), but their use has not advanced to becoming a basic part of the industry safety culture.

Airline safety has benefited greatly from comprehensive *reactive* accident investigations. As the industry transitions to increased dependence on autonomous systems, advanced QRA methods can provide near-term added value to the safety and economic performance of air travel. The result is added clarity of critical interactions between system elements (hardware, software, and human) and accountability of nonlinearities.

The Triplet Definition of Risk

The framework for quantifying risks that has been very successful in many industries and adopted by some regulatory agencies is the “triplet definition of risk” (Kaplan and Garrick 1981). This definition is founded on the principle that when one asks “what is the risk of something” they are really asking three questions:

- What can go wrong?
- How likely is it to go wrong?
- What are the consequences?

The first question is answered by a set of scenarios, the second by the available evidence accounting for the

² Correspondence between B. John Garrick and Tom Wellock, historian, US Nuclear Regulatory Commission, about early probabilistic risk assessment development activities, March 18, 2016.

³ A scenario is a sequence of events starting with an initiating or triggering event, going through all possible aggravating or mitigating events or conditions, and resulting in either success or adverse consequences.

uncertainties, and the third by the various end states of the scenarios.

Formally, this is written as a complete set of triplets:

$$R = \{ \langle S_i, L_i, X_i \rangle \}_c,$$

where R denotes the risk attendant to the system or activity of interest, S_i denotes risk scenario i , L_i denotes the likelihood of that scenario, and X_i denotes the consequences or damage level of the scenario. The angle brackets $\langle \rangle$ enclose the triplet, the curly brackets mean “a set of,” and the subscript c denotes complete, meaning that all of the important scenarios are included in the set. This notion of risk can be generalized to any metric of performance of the system being analyzed.

The rigorous risk assessment methods proposed for alert systems are the triplet definition of risk in conjunction with the theory of scenarios, the hybrid causal logic (HCL) method, and methods of human reliability analysis (cognitive and behavioral sciences, simulation, experimental validation). A key assessment requirement is a characterization of the pilot response to resolution advisories (RAs).

*Rigorous risk assessment
methods proposed
for alert systems include
characterization of
pilot response to
resolution advisories.*

The HCL method (Groth et al. 2010) is a multi-layered structure that integrates event sequence diagrams (ESDs), fault trees, and Bayesian networks (BNs). This hybrid modeling capability allows appropriate modeling techniques for different aspects of the system or process and their environment.

In the HCL approach, risk scenarios are modeled in the first layer using ESDs. Fault trees are used in the second layer to model the response behavior of the physical system as possible causes or contributing factors to the events delineated by the ESDs. The BNs in the third layer extend the causal chain of events to potential human, organizational, and process roots, and prob-

ability of failure models for equipment. Other layers of analysis are added as appropriate. For the TCAS example, an additional layer models the interactions between air traffic control (ATC), the TCAS, and the pilot. The results are used to aid risk management activities.

The QRA process generally involves the following:

1. Define the system being analyzed in terms of what constitutes successful operation.
2. Structure and process scenarios for both “success” and “what can go wrong.”
3. Quantify the scenarios while characterizing their uncertainties.
4. Assemble and integrate the scenarios into definitive risk metrics.
5. Interpret the results to aid the risk management process.

The following example emphasizes steps 1 and 2, which capture the framework of QRA and are foundational to the computational steps 3 and 4. The critical TCAS components of detection, evaluation and response, and pilot execution are represented in the logic models developed for steps 1 and 2. The goal is to perform the types of analyses on alert systems that could reduce the risks of such disasters as currently attributed to faults in the Boeing 737 MAX MCAS (Baker 2019).

Illustrative Example: TCAS

This example uses the following assumptions:

1. The intruding aircraft’s TCAS and pilot are performing according to specifications and procedures.
2. This scenario is taking place in midair at cruising altitude (35,000 feet). There are no geographical or meteorological factors in play.
3. No other aircraft are in close vicinity of the two under consideration.
4. The only entities under fault consideration are the TCAS, the pilot, and the aircraft.

Define the System

The TCAS mitigates collision risk by surveilling and tracking nearby air traffic and issuing avoidance instructions (RAs and traffic advisories) to pilots when a threat is determined.

A Mode-S transponder regularly sends out location information around a particular range. When the signal is received, the TCAS logic unit processes the information, which contains data about the other aircraft, typically the heading (direction), speed, altitude, posi-

tion, and the aircraft’s unique identification code. The logic unit begins a series of “interrogations” using the transponder directed toward the other aircraft with the unique address. Thus both aircraft have information about each other. There are three intruder aircraft TCAS detection regions around the aircraft—the caution area, warning area, and collision area, as illustrated in figure 1.

When the intruder aircraft enters the RA zone, the TCAS increases the frequency of interrogation and issues RAs to both pilots in the form of a red dot on the display and an audio announcement of commands directing the pilot to execute a standard maneuver. For example, the command “climb, climb” directs the pilot to climb at a rate of 1,500 to 2,000 feet per minute. The TCAS of both aircraft would now issue RA commands and inform the TCAS of the other aircraft to synchronize decision making.

Structure and Process Scenarios for Success and Failure

Success and failure states of the system are defined using logic tools such as an event sequence diagram. An ESD for the TCAS is illustrated in figure 2.

From the moment two planes enter each other’s RA zone, the ESD describes several scenarios. Ideally, the TCAS provides the optimal solution; a successful end state (denoted “safe” in the figure) is where both planes maneuver to safety. Multiple failure end states are represented by different colors. Dotted lines indicate extensions in the sequence.

An example scenario based on the ESD is described by the yellow lines in figure 2. The scenario tries to break down the events that led to the 2002 Überlingen midair collision.⁴ Starting at the initiating event, the intruder aircraft (DHL flight 611, a Boeing 757 cargo jet) enters the threshold zone of Bashkirian Airlines

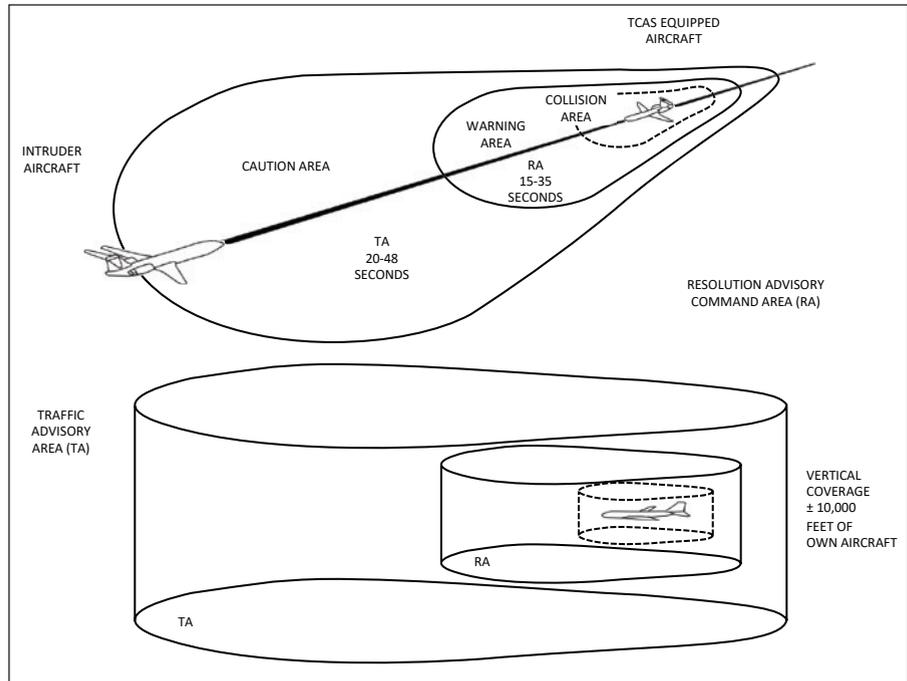


FIGURE 1 Traffic advisory (TA) and resolution advisory (RA) ranges for an intruding aircraft. Adapted from FAA (2011).

flight 2937 (a Tupolev Tu-154 passenger jet) for issuing RAs. TCAS computes the correct steps for safety and sends the information to the pilot of the Tu-154, but ATC relays the wrong instructions to the same pilot. The pilot thus has conflicting instructions from the TCAS and ATC, forcing him to choose between the two advisories with limited visual information to evaluate them. The pilot decides to follow the ATC instructions and maneuvers the aircraft accordingly. Since the other pilot is following TCAS (as in the scenario and assumptions), both aircraft execute descend maneuvers, resulting in a midair collision.

Causes of TCAS failure fall into two categories: the TCAS or pilot response. TCAS failures may involve sensors, transponder-interrogating systems, ground-based primary and secondary surveillance radars, and automatic dependent surveillance–broadcast (ADS-B). Airborne transponder-interrogating systems provide air-to-air surveillance of other transponder-equipped aircraft. Alternatively, ground-based radars can provide surveillance information via a digital datalink. ADS-B relies on aircraft self-reporting their position as determined by GPS or some other navigation system.

Pilot errors include response error, failure to understand the alert, failure to assign priority to an alert,

⁴ https://en.wikipedia.org/wiki/2002_Überlingen_mid-air_collision

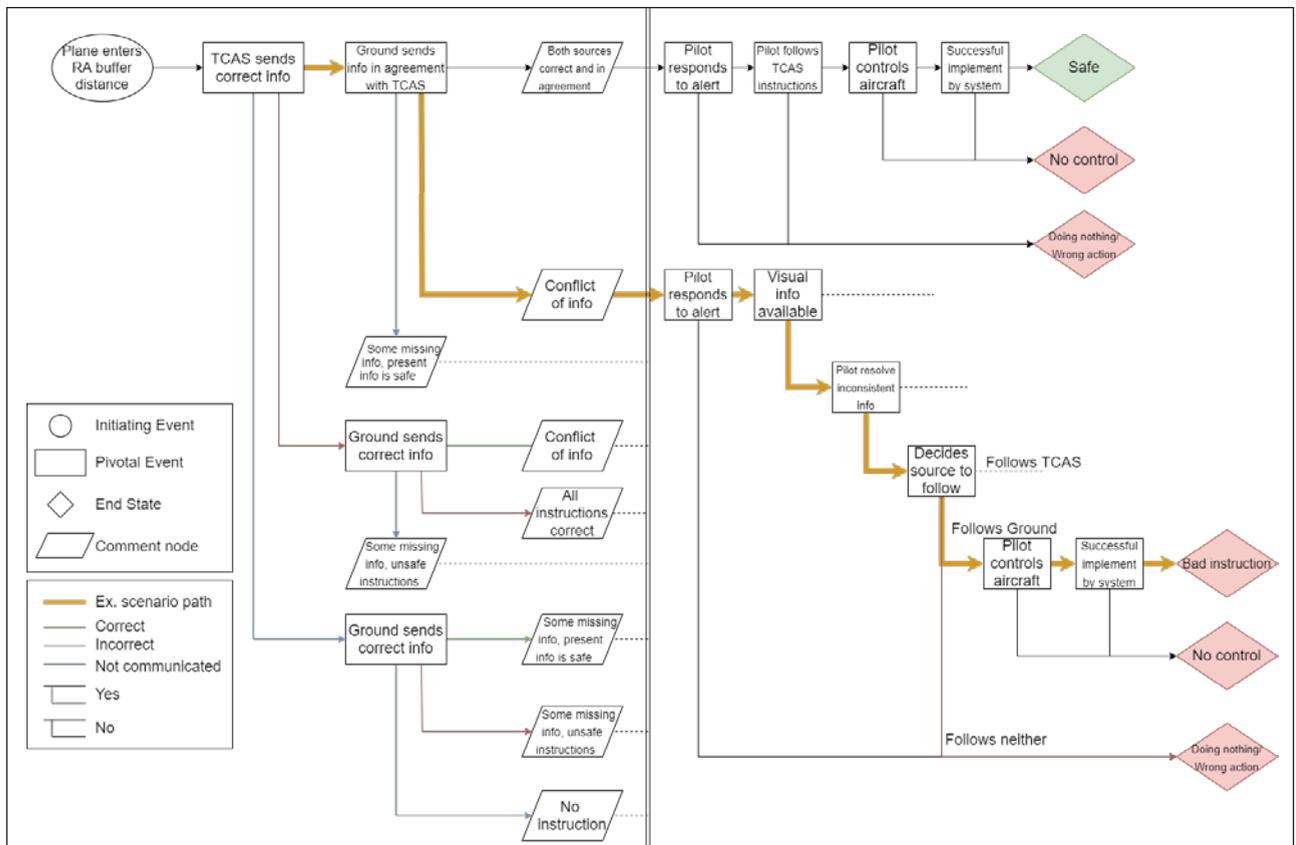


FIGURE 2 Event sequence diagram (ESD) for the response of the traffic alert and collision avoidance system (TCAS) and pilot when an intruding aircraft enters the resolution advisory (RA) zone. Example (ex.) sequence highlighted in yellow; dotted lines indicate extensions in the sequence.

failure to select the appropriate action, and failure to comply with the alert.

In addition to the three layers of the HCL model, another layer models the interactions between the system (all hardware and software) and the pilot, using the concurrent task analysis (CoTA) method (Ramos et al. 2020). This is the first application of the CoTA method in the context of aviation safety.

The CoTA, developed from the system's ESD, is a success-oriented model that allows for a more detailed understanding of the tasks that must be accomplished for the ESD events to take place. It translates the events from the ESD to specific tasks in three categories: TCAS, pilot, and aircraft. Logically all three sets are part of the same CoTA scenario. The development of the scenario-specific CoTA starts with identification of the events involved in the selected ESD path. The analyst then highlights the human task actions that belong to that sequence.

Figure 3 shows a TCAS task using CoTA modeling. The TCAS collects information and communicates

with the pilot in parallel with all other tasks. The TCAS tasks do not show up on the ESD as they are parallel, nonsequential tasks that appear only in CoTAs. Because some pilot actions (such as response to an alarm) depend on TCAS communication and data collection tasks, outgoing interface nodes for human task actions are linked to these tasks.

The pilot CoTA shown in figure 4 shows one of the pilot tasks after a TCAS alert. The pilot must respond to the alert, process available information, and make a decision about which actions to take, all while constantly monitoring the situation using information from TCAS, ATC, and visual senses.

Fault trees can be linked to CoTA events to show failure in a single task. Interfaces between tasks can be added as extensions to the fault trees. As an example, failure of the pilot task "Resolve incorrect or inconsistent info" is modeled using the Phoenix method (Ekanem et al. 2016) in the fault tree of figure 5. Phoenix is a human reliability analysis method that identifies and quanti-

fies the probability of possible human errors in interactions with complex systems. Errors are analyzed for three distinct phases of human-system interactions: information gathering, situation assessment/decision making, and action execution. Since failure in task “Resolve incorrect or inconsistent info” represents a decision-making failure, it is broken down into a failure either to assess the situation or to decide on an action. In the Überlingen case, the failure was due to the pilot’s incorrect conclusion.

Performance-influencing factors (PIFs) that influence or cause human failure events (HFEs) identified in the human response fault tree can be modeled using BNs, an extension of the HFE fault tree for the HFE “inappropriate conclusion” (the yellow path in figure 5). These factors (e.g., knowledge/abilities, resources, stress, bias, time constraint) can each play a role in the pilot’s misdiagnosis. For example, in the 2002 Überlingen midair collision, TCASs were new and not well established. This would create a strong bias in favor of the information provided by ATC.

The BN extension in figure 5 is taken from the Phoenix human reliability model but not all PIFs are included. The justification for including or removing individual PIFs is given in table 1 based on how each PIF would affect the pilot’s decision making.

System failures are also modeled through corresponding hardware fault trees. Once the full model is constructed using the steps illustrated above, it needs to be processed using mathematical and computational

TCAS response

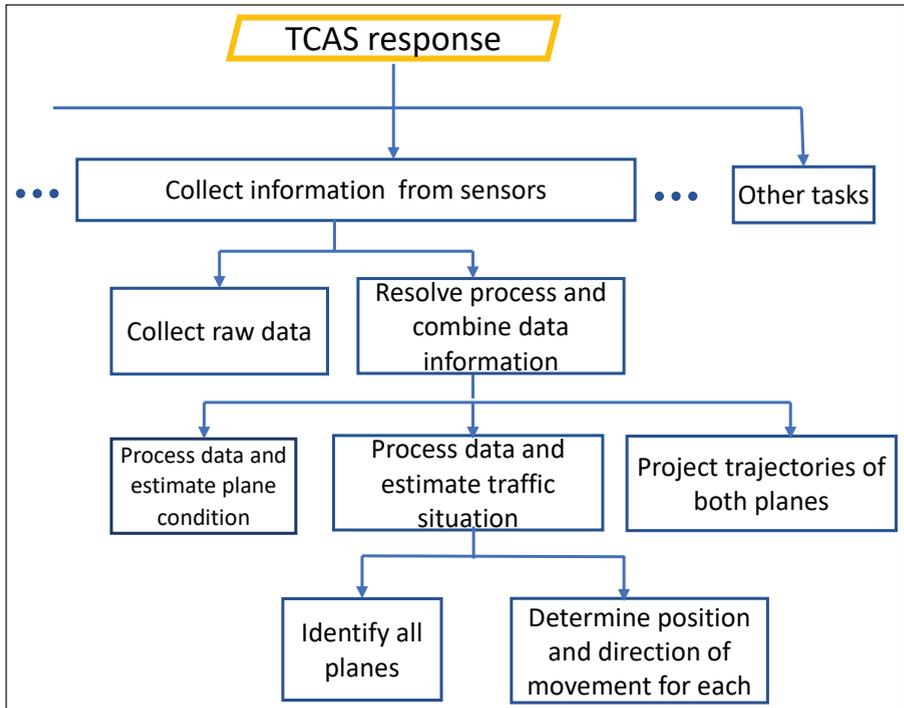


FIGURE 3 Traffic alert and collision avoidance system (TCAS) concurrent tasks.

Pilot response

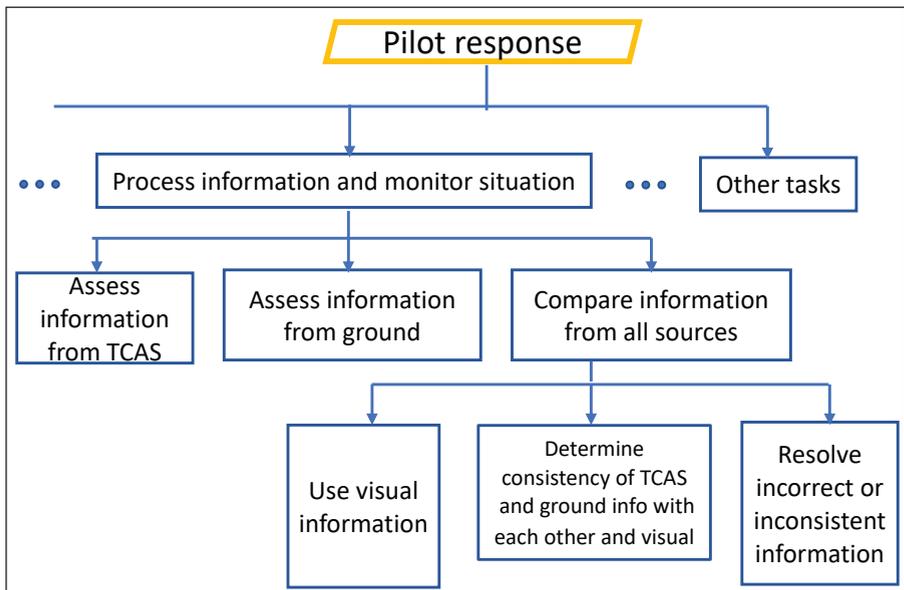


FIGURE 4 Pilot concurrent tasks. TCAS = traffic alert and collision avoidance system.

procedures to identify risk scenarios and contributing factors. For example, the highlighted (yellow) path in figure 2 and contributing events highlighted in figure 5 form a scenario.

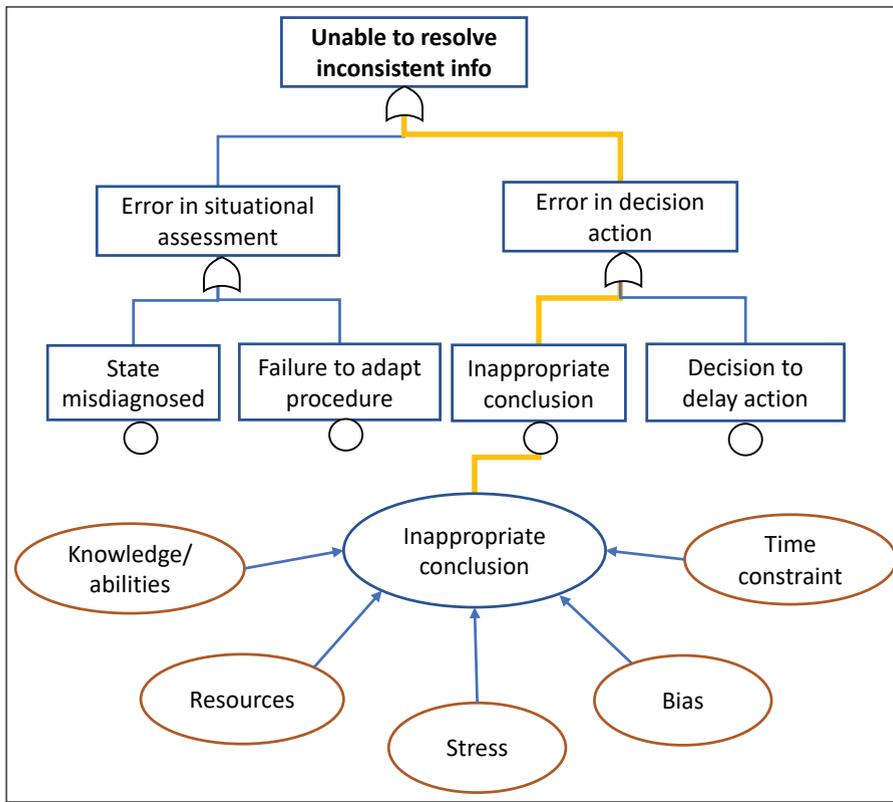


FIGURE 5 Segment of pilot error model using Phoenix human reliability analysis method.

Quantify Scenarios and Characterize Their Uncertainties

The probability, $p(s)$, of any given risk scenarios is the product of the conditional probabilities, $P(E_i)$, given the events (E_0, E_1, \dots, E_N) , forming the scenario:

$$p(s) = \prod_{i=1}^N P(E_i | E_0, E_1, \dots, E_{i-1})$$

The failure probabilities (hardware, software, or human) are estimated based on all available evidence. Advanced quantitative risk assessments use Bayesian inference methods for estimation of the risk model parameters including probabilities and rates of events. The main reason is that failures and accidents in highly reliable and safe systems are rare, forcing the analyst to use partially relevant evidence, generic data, or expert subject-matter knowledge.

Bayes' theorem is

$$P(x/E) = P(x) \frac{P(E/x)}{P(E)}$$

where x is the event or quantity of interest, $P(x)$ the initial or prior probability of x , $P(x/E)$ the posterior or updated probability of x given any available data or evi-

dence E , and $P(E/x)$ the likelihood of the evidence given an assumed value of x .

Essential to any credible risk analysis is a comprehensive characterization and quantification of uncertainties: aleatory, epistemic, parametric, or modeling.⁵ Advanced QRA methods allow these uncertainties to be identified and quantified during modeling and quantification of the risk scenarios.

Assemble and Integrate Scenarios in Interpretable Risk Metrics

Before performing a risk assessment, a decision has to be made about the consequences to be quantified and the desired form of the risk metric. Typical consequences are the failure of a system to perform its intended function, physical damage, injuries, fatalities, or a combination

of these. Typical risk metrics are probability, frequency, or a combination such as probability of frequency; the frequencies are represented by probability distributions to account for their uncertainties.

For complex systems the number of scenarios could be millions, thus the need for assembling the results in a form that captures the full story for interpretation. Frequency of exceedance curves of the type shown in figure 6 can be developed for each consequence of interest and is constructed by ordering the scenarios by increasing levels of damage and cumulating the probabilities from the bottom up, with probability P represented as a family of curves. The form of the result on log-log paper is figure 6, which illustrates that there is a

⁵ Uncertainties can be characterized by the following types:

- *Aleatory*: natural or inherent randomness or stochastic nature of the phenomena being analyzed; this type of uncertainty is considered irreducible
- *Epistemic*: uncertainty due to limitations in knowledge; considered reducible by increasing knowledge, data, or evidence
- *Parametric*: uncertainty about the individual parameters of the model
- *Modeling*: uncertainty about the structure and completeness of the model(s).

TABLE 1 Performance-influencing factors (PIFs) involved in a human failure event, “inappropriate conclusion”

| PIF | Human system int. | Procedure | Resources | Team effectiveness | Knowledge/abilities | Stress | Bias | Task load | Time constraint |
|---------------|--|--|--|--|---|---|---|---|---|
| Included? | No | No | Yes | No | Yes | Yes | Yes | No | Yes |
| Justification | No interactions with the interface are occurring in this event | No procedure is being used to make this decision | Availability and quality of other resources such as visual information | Success of this task needs only the response of one individual | The pilot’s experience and training will influence their decision | Stress may increase the chance of making a hasty or poor decision | Having bad experiences with TCAS or ground may cloud the pilot’s decision process | The pilot has already noticed the alarm and should be focused on it at this stage | Limited time could lead to a hasty decision |

P_3 probability that a consequence of X_1 or greater has an annual frequency of Φ_1 . The family of curves also facilitates presentation of the results in terms of confidence intervals if desired.

Risk metrics provide insights and guidance not only on design, operational, and maintenance measures for reducing risk but also for training and qualification of personnel such as pilots and for recovery from life-threatening events.

Concluding Remarks

The above modeling and process steps illustrate that comprehensive and rigorous quantitative risk models are possible for safety-critical aircraft systems and can contribute to air travel safety. The proactive methods involve the processing of direct and indirect evidence, accountability of system hardware and software logic and dynamics, human performance analysis, and the ability to simulate large numbers of concurrent tasks. Typical output is a ranked list of risk scenarios and contributors by probability and consequence.

The methodology used in this paper to illustrate the essential steps of QRA of complex systems, while quite advanced and powerful in providing risk insights, may still be inadequate to capture the complexity of some systems. Advanced simulation-based methods (Mosleh 2019) have proven to be particularly effective for systems with control loops and complex interactions between elements—hardware, software, or human; they provide a natural probabilistic environment with physical models of system behavior (e.g., coupled processes), mechanistic models of materials or hardware systems to predict failure, and models of natural hazards. Simulation-based methods are expected to play a critical role in the assessment of autonomous systems (e.g., aircraft, ocean vessels, and ground vehicles) with humans transitioning toward a monitoring and recovery role.

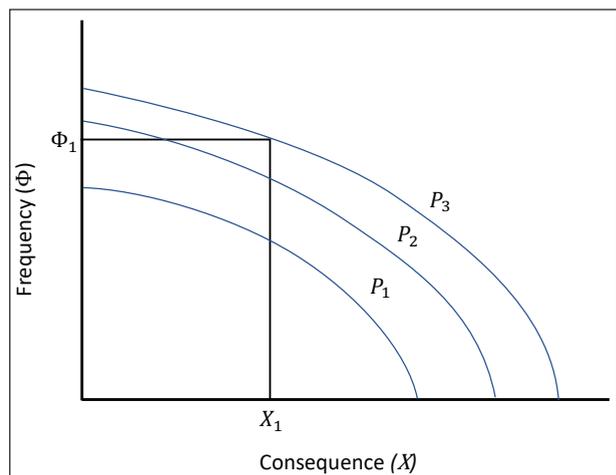


FIGURE 6 Risk as a function of consequence severity.

Acknowledgments

The authors acknowledge significant contributions of UCLA Garrick Institute research scientist Marilia Ramos and graduate students Karthik Sankaran and Theresa Stewart in developing the example application.

References

Baker M. 2019. The inside story of MCAS: How Boeing’s 737 MAX system gained power and lost safeguards. Seattle Times, Jun 22 (updated Jun 24).
 Ekanem N, Mosleh A, Shen SH. 2016. Phoenix—A model-based human reliability analysis methodology: Qualitative analysis procedure. Reliability Engineering & System Safety 145:301–15.
 FAA [Federal Aviation Administration]. 2011. Introduction to TCAS II Version 7.1. Washington.
 Garrick BJ. 2008. Quantifying and Controlling Catastrophic Risks. Amsterdam: Elsevier.
 Garrick BJ. 2014. PRA-based risk management: History and perspectives. Nuclear News 57(8):48–53.

- Groth K, Wang C, Mosleh A. 2010. Hybrid causal methodology and software platform for probabilistic risk assessment and safety monitoring of socio-technical systems. *Reliability Engineering & System Safety* 95:1276–85.
- Kaplan S, Garrick BJ. 1981. On the quantitative definition of risk. *Risk Analysis* 1(1):11–27.
- Kuchar J, Andrews J, Drumm A, Hall T, Heinz V, Thompson S, Welch J. 2004. Safety analysis process for the traffic alert and collision avoidance system (TCAS) and see-and-avoid systems on remotely piloted vehicles. Presented at AIAA 3rd “Unmanned Unlimited” Technical Conf, Workshop, and Exhibit, Sep 20–23, Chicago.
- Mosleh A, Groth K, Wang C, Groen F, Hzu D. 2007. Integrated Risk Information System, Methodology and Software Platform developed for the US Federal Aviation Administration by the University of Maryland Center for Risk and Reliability.
- Mosleh A. 2019. Architecture for guided simulation of probabilistic evolution of complex systems. Publication of the UCLA B. John Garrick Institute for the Risk Sciences (GIRS-2019-10/L). Available from GIRS.
- NASEM [National Academies of Sciences, Engineering, and Medicine]. 2014. *Lessons Learned from the Fukushima Nuclear Accident for Improving Safety of US Nuclear Plants*. Washington: National Academies Press.
- PLG [Pickard, Lowe, and Garrick, Inc.], Westinghouse Electric Corporation, Fauske and Associates, Inc. 1981. Zion probabilistic safety study. Prepared for Commonwealth Edison Company, Chicago.
- PLG, Westinghouse Electric Corporation, Fauske and Associates, Inc. 1982. Indian Point probabilistic safety study. Prepared for Consolidated Edison Company of New York and New York Power Authority.
- PLG. 1989. Beznau Station Risk Assessment: Plant with NANO (PLG0511). Prepared for and available from Nordostschweizerische Kraftwerke AG, Zürich.
- Ramos MA, Thieme CA, Utne IB, Mosleh A. 2019. Autonomous systems safety: State of the art and challenges. *Proceedings, First Internatl Workshop on Autonomous Systems Safety*, Mar 11–13, Trondheim, Norway.
- Ramos MA, Thieme CA, Utne IB, Mosleh A. 2020. Human-system concurrent task analysis for maritime autonomous surface ship operation and safety. *Reliability Engineering & System Safety* 195:106697.
- Spouge J. 1999. *A Guide to Quantitative Risk Assessment for Offshore Installations*. Aberdeen UK: Centre for Marine and Petroleum Technology.
- Stamatelatos M, Dezfuli H. 2011. *Probabilistic Risk Assessment Procedures Guide for NASA Managers and Practitioners (NASA/SP-2011-3421, 2nd ed)*. Washington: NASA Headquarters.
- USNRC [US Nuclear Regulatory Commission]. 1975. *Reactor Safety Study: An Assessment of Accident Risks in US Commercial Nuclear Power Plants (WASH-1400, NUREG-75/014)*. Washington.

Advances in technology, computing, and AI point the way forward for the incorporation of greater autonomy in aviation.

Some Steps toward Autonomy in Aeronautics



J-P. Clarke



Claire Tomlin

John-Paul B. Clarke and
Claire J. Tomlin

In aeronautics, the word “autonomy” engenders visions of a future in which aircraft are able and allowed to operate in civil airspace independent of human control or supervision—without pilots or ground-based operators/supervisors, interacting with air traffic controllers (which may themselves be machines) and other pilots just as if a human pilot were on board and in command (NRC 2014).

Background

Broadly speaking, an autonomous machine system has a degree of self-government and self-directed behavior based on artificial intelligence (AI)-based capabilities that allow it to respond to situations that were not preprogrammed or anticipated in the design (i.e., decision-based responses) (Masiello 2013). All aircraft have systems with varying levels of automation—unless they fail or malfunction, these systems can and do operate without continuous human oversight. Increasingly autonomous systems could allow both crewed and uncrewed aircraft to operate for extended

J-P. Clarke is Dean’s Professor in the Daniel Guggenheim School of Aerospace Engineering and the H. Milton Stewart School of Industrial and Systems Engineering at the Georgia Institute of Technology. Claire Tomlin (NAE) holds the Charles A. Desoer Chair in Engineering as a professor in the Department of Electrical Engineering and Computer Sciences at the University of California, Berkeley.

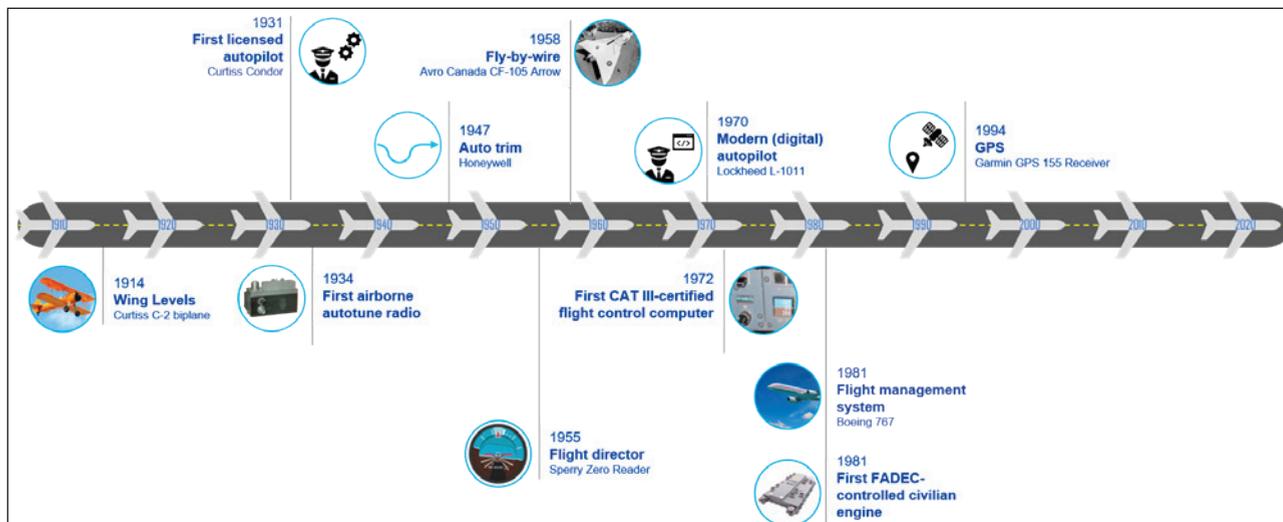


FIGURE 1 Selected history of automation in civilian aeronautics. CAT = category; FADEC = full-authority digital engine control. Source: Clarke (2019).

periods without the need for humans to monitor, supervise, and/or directly intervene in the operation of those systems in real or near-real time (NRC 2014).

Reducing and eventually eliminating the need for continuous human cognizance and control would enable reductions in crew complements and the associated direct operating cost of passenger and cargo aircraft, and enable both crewed and uncrewed aircraft to take on new roles not previously possible, practical, or cost-effective.

Overview of Autonomy in Aircraft Systems

The rich history of autonomy in air is punctuated by several key advances, typically developed and tested in military aircraft and then adopted in civilian aircraft (figure 1). The first steps in autonomy date back more than 100 years to levelers in the early biplanes that used hydraulically operated ailerons, elevators, and rudders.

While civilian and military aviation have much in common historically with respect to autonomy, there has been some deviation in recent decades with the increased use of remotely piloted drones as platforms for surveillance and/or attack (it is important to note, however, that no automated system would ever “make the decision” to kill—there must be a human in the decision loop).

Today’s fast computation and communication, and advances in AI and machine learning, augur a new era of autonomy. However, understanding how to develop

and deploy these tools for safety-critical systems is still in its infancy. Effective partnerships of AI and machine learning methods with pilots, other aircraft operators, and air traffic controllers are crucial for their safe deployment in aircraft. Just as the era of modern control was heavily influenced by aeronautics in the last century, aeronautic autonomy in this century could turn out to be the impetus for the design of safe learning and productive human-AI partnerships.

Research Needs

If aircraft are to be operated unattended, increasingly autonomous systems must be able to perform critical functions currently done by humans, such as “detect and avoid,” performance monitoring, subsystem anomaly and failure detection, and contingency decision making. This requires an understanding of how humans perform their roles in the present system and how these roles may be transferred to an increasingly autonomous system, particularly in high-risk situations, as well as a system architecture that supports intermittent human cognizance and control.

Further, because aircraft operate in uncertain environments and increasingly autonomous systems may have subsystems and components with whole or partially stochastic behavior, mathematical models are needed to describe

- adaptive/nondeterministic processes as applied to humans and machines;

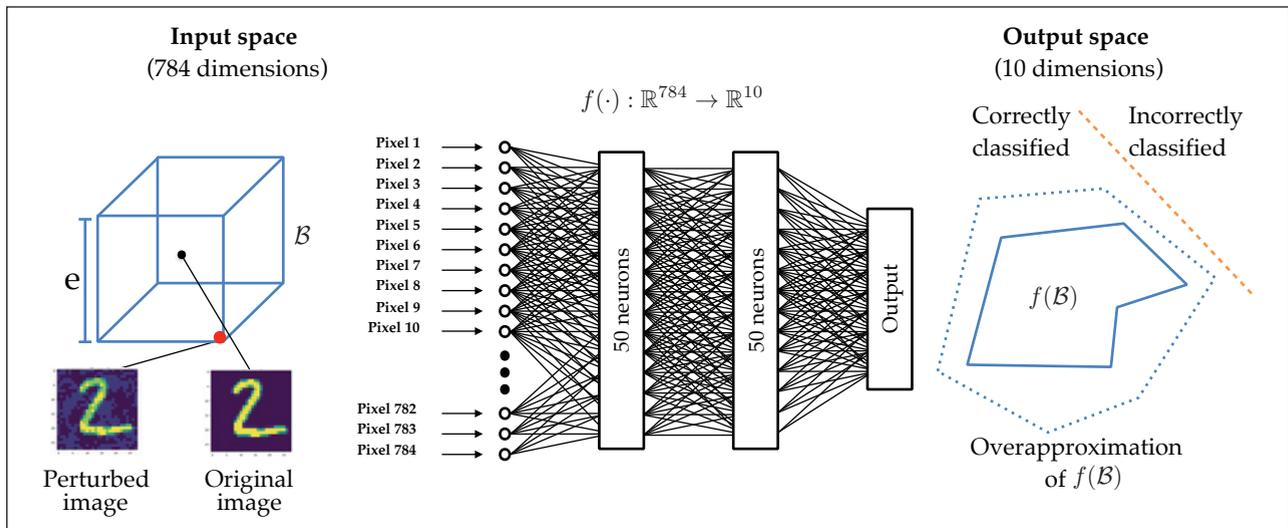


FIGURE 2 For the image verification task, a region B around a specific image is tested to ensure that, for every image within B , the correct classification is achieved. Figure courtesy of Vicenç Rubies-Royo.

- performance criteria, such as stability, robustness, and resilience, for the analysis and synthesis of adaptive/nondeterministic behaviors; and
- methods beyond input-output testing for characterizing the behavior of increasingly autonomous systems.

Safety in Learning-Enabled Perception

One of the challenges in autonomous aviation is automated perception-based control—interpreting sensed information and providing an appropriate, safe control action. Current safety analysis tools enable autonomous systems to “reason” about safety given full information about the environment (Ames et al. 2017; Kousik et al. 2018; Mitchell et al. 2005). However, these tools do not scale well to scenarios in which the environment is being sensed in real time, such as during autonomous navigation tasks.

Moreover, perception itself is a challenge: the state of the art in object detection uses learning-based components, such as neural networks, yet such systems can produce solutions that are brittle to faults and cyber-attack. Tools that analyze and quantify the correctness of such learning-based components and that provide a safe control action are needed. In the last two years, the need for such tools has been recognized with DARPA’s Assured Autonomy program¹ and NASA’s University Leadership Initiative in Assured Autonomy for Aviation Transformation (Balin 2016).

¹ <https://www.darpa.mil/program/assured-autonomy>

Neural Networks for Aircraft Perception

Consider a neural network in a future aircraft flight management system. Connected to a set of cameras on the aircraft, it takes sequences of images as its input, and its output is information critical for planning and control, such as location and type of other vehicles in the vicinity of the aircraft. Correct identification and localization are paramount for safety, as is prediction of the behavior of the other vehicles.

Recent progress has been made in assessing the correctness and robustness of decision analysis of neural networks through input-output verification and adversarial analysis, testing input data for typicality against a learned distribution of the training data, and designing a control policy to provide safe control action despite uncertainty in the vehicle’s environment.

Input-Output Verification

Input-output verification of neural networks has for the most part been applied to classification problems, such as image classification. It starts with the definition of an allowable input set (e.g., all small perturbations of a given image) and then seeks to determine whether there exists an allowable input to the neural network for which the output is incorrect—that is, whether the neural network makes a mistake in classification.

This process can be seen in figure 2, in which an image of the written number “2” from the MNIST database of handwritten digits² is input to a network that attempts

² <http://yann.lecun.com/exdb/mnist/>

to correctly classify it as the digit “2.” The input-output verification problem asks if there exists an image within a distance of “ ϵ ” in pixel space of this image (region B in figure 2), which is classified incorrectly. This problem is extremely challenging because of the high-dimensional input space as well as the large number of nodes and connections in the neural network (Katz et al. 2017).

There have been exciting recent developments in approximate solutions, though—ones that generate fast overapproximations of the set of possible neural network outputs and ask if such outputs would be misclassified (Bunel et al. 2018; Rubies-Royo et al. 2020; Singh et al. 2018; Wang et al. 2018; Zhang et al. 2018). Figure 2 illustrates the idea: if a quickly computed overapproximation of the neural network’s response to B — $f(B)$ in figure 2—is among the outputs that are all classified correctly as “2,” then all images in the region B are classified correctly as “2.” Yet even with these advances, input-output verification is limited to small images.

*Techniques for
fast approximation and
safe contingency analysis
will be crucial in the
real-time environment
of aviation.*

New ways of thinking about the verification problem are needed—perhaps techniques that use image structure from cameras on the aircraft to reduce the system dimension.

The Need for Redundancy

Finally, despite the advances in learning-based perception, assured autonomy should continue to rely on the use of parallel and redundant sensor suites. For example, we have proposed a novel, real-time safety analysis method based on Hamilton-Jacobi reachability that provides strong safety guarantees despite environment uncertainty (Bajcsy et al. 2019). This safety method uses real-time measurements from a second sensor, which complements the vision sensor, to compute and update a safe operating envelope.

While promising, scaling such methods for use in the real-time environment of aviation is still a challenge, and techniques for fast approximation and safe contingency analysis will be crucial.

Human-Machine Teaming in Aeronautic Autonomy

Interactions between humans and machines are increasingly moving away from a “human use of machines” paradigm to the establishment of “relationships between humans and autonomous automated agents.” Optimal human-machine teaming (HMT), where the role of and relationship between humans and machines are optimized based on their individual and collective capabilities, is critical to achieving safe and efficient (economic and environmental) operations (Clarke 2019).

Enhanced Pilot Support

HMT is a critical enabler of single-pilot operations (SPO; also known as reduced-crew operations, RCO), an active area of study by NASA (Bilimoria et al. 2014). In commercial aviation, RCO is increasingly being considered as a viable solution to the rising costs associated with commercial air transport.

Recent advances in communications, navigation, surveillance/air traffic management, and avionics technologies have enabled higher levels of automation, which might be leveraged to mitigate the elevated workload of a single pilot. For example, pilots could be provided with higher levels of decision support for the execution of complex tasks, or with a highly autonomous automated agent that is akin to a copilot in terms of being a partner as opposed to merely executing preprogrammed functions.

Recent RCO research has focused on ground-based support, loss of the redundancy of a copilot, pilot health monitoring, aircraft systems monitoring, takeover and handback of control, recovery from an airside loss of control, pilot boredom, and certification (Schmid and Stanton 2019). Ultimately, in-flight mitigation strategies will have to be reconsidered and specifically tailored for RCO/SPO with respect to advanced automation tools and their reliability (Schmid and Stanton 2020). For example, a cognitive pilot-aircraft interface concept has been proposed with adaptive knowledge-based system functionalities to assist single pilots in the accomplishment of mission- and safety-critical tasks in commercial transport aircraft (Liu et al. 2016).

The Loyal Wingman Program

One very notable effort in military HMT is the loyal wingman program: a manned-unmanned teaming (MUM-T) concept in which a UAV flies in formation with a piloted vehicle, but may be separately tasked to break and rejoin formation as the mission dictates under the tactical command of the piloted lead (Humphreys et al. 2015). This is the latest evolution of MUM-T efforts in the US Air Force (James and Welch 2014; USAF Chief Scientist 2010; Winnefeld and Kendall 2011, 2013).

A significant portion of Air Force Research Laboratory research on autonomy for the loyal wingman has focused on solving optimal control problems in near-real time (Humphreys et al. 2015), using techniques such as direct orthogonal collocation (Humphreys et al. 2017). Internationally, there are similar loyal wingman-type efforts underway in Australia (Pittaway 2019), China (Mizokami 2019), and France (Fiorenza 2018).

Importance of Human Understanding of Autonomous Systems

The US Air Force is working to develop systems where humans have sufficient trust in intelligent machines that the latter are allowed to perform more of the tasks required to operate an aircraft (Overholt and Kearns 2014). Recent research results indicate that

- the better humans understand the decision-making process of a machine, the more they trust it (Knight 2017; Lyons et al. 2016; Wang et al. 2015);
- training can improve human-machine trust by helping human operators understand the limits of the capabilities of an autonomous machine (Lyons et al. 2016);
- HMT is most effective when tasking is broken down hierarchically (Daniels 2017); and
- emphasis should be on determining which input modalities are optimal for specific types of tasks or application environments, rather than spending resources to implement multiple modalities across all tasks (Zacharias 2019).

HMT and Urban Air Mobility

HMT is also critical in the burgeoning domain of urban air mobility (UAM). The economics of air taxi operations do not support the employment of human operators that are trained—and thus compensated—at the same rates as commercial pilots. Thus, there will be

a greater role for autonomy than is currently the case in commercial or general aviation.

Furthermore, because rapid decision making and action are critical in flight vehicles that operate in close proximity to structures and people as well as in an environment with rapidly changing winds, passenger and cargo aircraft will have to be designed for both autonomous operations (i.e., without continuous human participation or supervision) and autonomous decision making (i.e., with the ability to determine what to do next in an unscripted situation without needing to consult a human). The same will be true for remotely operated aircraft with time delays between the operator and the aircraft (due to distance between them) and periodic loss of communication (due to line-of-sight blockage by buildings).

Analysis and Verification of Nondeterministic Systems

Aircraft operate in uncertain environments where physical disturbances, such as wind gusts, are probabilistic in nature. Further, distributed sensor systems—which supply the data that are transformed into the information on which pilots rely for decision making and control—have inherent noise with stochastic properties such as uncertain biases, random drifts over time, and varying environmental conditions.

*The better humans
understand the
decision-making process
of a machine,
the more they trust it.*

Safety Challenges of Closed-Loop Adaptive Systems

As increasingly autonomous systems—which take advantage of evolving conditions and past experience to adapt their behavior (i.e., they are capable of learning)—take over more functions traditionally performed by humans for the sake of improved efficiencies, there will be a need to analyze, verify, validate, and certify their behavior a priori, and to incorporate autonomous monitoring and other safeguards to ensure continued appropriate operational behavior. Thus,

there is tension between the benefits of incorporating software with adaptive/nondeterministic properties in increasingly autonomous systems and the requirement to test such software for safe and assured operation.

Research is needed to develop new methods and tools to address the inherent uncertainties in airspace system operations and thereby enable more complex adaptive/nondeterministic systems that can improve their performance over time and provide greater assurance of safety.

*Research is needed to
develop new methods and
tools to address the inherent
uncertainties in airspace
system operations.*

Guaranteeing the safety of closed-loop adaptive systems represents a formidable challenge. One need only look at personal experience to realize that learning does not necessarily proceed without hurdles (learning how to ride a bicycle, use skis, or windsurf typically entails accidents on the way to success).

From a fundamental dynamical system theory viewpoint, it is necessary to determine whether systems will (i) go “out of control” or (ii) function as desired. While failure to answer (i) is unacceptable from a verification perspective, answering (ii) and providing bounds, deterministic or probabilistic, on behaviors of adaptive systems can often be sufficient to verify the safety of models of a closed-loop adaptive system.

Run-Time Assurance

In the absence of generic knowledge about the safety of learning algorithms (there are a multitude of specific cases of adaptive systems whose behaviors are very well understood and safe; Boussios 1998), a partial remedy is to rely on run-time assurance (RTA) techniques (Sha 2001).

Run-time assurance is the practice of deferring the detection of dangerous behaviors until they happen and triggering corrective actions when they do. It has been used in multiple applications (e.g., emergency braking for elevators) and over time the definition of requirements for its correctness and power has improved

(e.g., Adams 2019; Dershowitz 1998; Schouwenars et al. 2005).

Recent operational implementations of RTA include the Automatic Ground Collision Avoidance System (Auto-GCAS), which automatically takes over pilot control in case of pending collision with the ground (Hobbs 2020). Little known is the Boeing 777 autopilot, whose behavior was considered sufficiently uncertain to be “bounded” by a better-known derivative of the Boeing 747 autopilot, ready to take over in case of erratic behavior (Hobbs 2020). In the future, RTA mechanisms similar to Auto-GCAS are likely to be developed to prevent collisions between spacecraft (Hobbs and Feron 2020).

One curious and attractive characteristic of RTA mechanisms is that they do not need the same kind of extensive certification as, say, an intelligent system in charge of the system’s operation. Indeed, the premise of run-time assurance is to constantly maintain an “option out” of behaviors recommended by primary intelligence. Verifying the validity of an “available option out” online is usually not complex.

The price of reduced verification requirements for run-time assurance is the need to mitigate false alarms (i.e., the RTA mechanism takes over regular operations when not needed). This problem may be mitigated by smarter RTA algorithms (Gurriet et al. 2018) or tolerated (to enable learning) if there are no significant short-term impacts on system performance.

Looking Ahead: Fully Autonomous Aerial Vehicles

There is immense interest in the use of fully autonomous aerial vehicles for commercial package delivery, surveillance, emergency supply delivery, videography, and search and rescue (Prevot et al. 2016), and of highly autonomous piloted and unpiloted air vehicles as “air taxis” for passengers in urban and regional environments. Projects such as Amazon Prime Air, Google Project Wing, Uber Elevate, and Airbus’s Vahana have been motivated in large part by technologies for automated control (Johnson and Kannan 2005), landing (Sharp et al. 2001), collision avoidance (Teo et al. 2005), and multiple vehicle cooperative operations (How et al. 2009) that were developed and tested over the past two decades in academic labs.

At the outset, these vehicles will fly well-defined routes in very predictable environments and will have automated all pilot functionality, including detect

and avoid, navigation in GPS-denied environments, autonomous contingency management, and obstacle detection and clear landing zone identification. Ultimately, learning-enabled perception, human-machine teaming, and verification of nondeterministic systems will be critical to make crewed and uncrewed operation in urban environments sufficiently safe for passenger and cargo operations and to enable full integration in the National Airspace System.

Acknowledgments

The authors acknowledge Eric Allison, Andrea Bajcsy, Somil Bansal, Alex Dorgan, Eric Feron, Keoki Jackson, Forrest Laine, Liling Ren, and Vicenç Rubies-Royo for providing information and perspectives in the writing of this article.

References

- Adams E. 2019. Cirrus' private jet can now land itself, no pilot needed. *Wired*, Oct 31.
- Ames AD, Xu X, Grizzle JW, Tabuada P. 2017. Control barrier function based quadratic programs for safety critical systems. *IEEE Transactions on Automatic Control* 62(8):3861–76.
- Bajcsy A, Bansal S, Bronstein E, Tolani V, Tomlin CJ. 2019. An efficient reachability-based framework for provably safe autonomous navigation in unknown environments. *arXiv* 1905.00532.
- Balin M. 2016. ARMD Strategic Thrust 6: Assured Autonomy for Aviation Transformation. NASA Aeronautics Vision and Roadmap Presentation, May 24. Online at <https://www.nasa.gov/sites/default/files/atoms/files/armd-sip-thrust-6-508.pdf>.
- Bilimoria KD, Johnson W, Schutte P. 2014. Conceptual framework for single pilot operations. *Proceedings, Internatl Conf on Human-Computer Interaction in Aerospace*, Jul 30–Aug 1, Santa Clara.
- Boussios C. 1998. An approach to nonlinear controller design via approximate dynamic programming. PhD thesis, Massachusetts Institute of Technology.
- Bunel RR, Turkaslan I, Torr PHS, Kohli P, Kumar MP. 2018. A unified view of piecewise linear neural network verification. *Conf on Neural Information Processing Systems*, Dec 3–8, Montreal.
- Clarke JP. 2019. Towards optimal human-machine teaming. Plenary talk, AIAA Intelligent Systems Workshop, Jul 29–30, Cincinnati. Online at <http://hdl.handle.net/1853/62917>.
- Daniels M. 2017. Artificial intelligence: What questions should DoD be asking? Center for Global Security Research Lecture Series, Nov 20. Livermore: Lawrence Livermore National Laboratory.
- Dershowitz AL. 1998. The effect of options on pilot decision making in the presence of risk. PhD thesis, Massachusetts Institute of Technology.
- Fiorenza N. 2019. DGA commissions man machine teaming studies. *Jane's Defence Weekly*, Nov 22.
- Gurriet T, Mote M, Ames AD, Feron E. 2018. An online approach to active set invariance. *Proceedings, IEEE Conf on Decision and Control*, Dec 17–19, Miami Beach.
- Hobbs K. 2020. Elicitation and formal specification of runtime assurance requirements for aerospace collision avoidance systems. PhD thesis, Georgia Institute of Technology.
- Hobbs K, Feron E. 2020. A taxonomy for aerospace collision avoidance with implications for automation in space traffic management. *AIAA Scitech Forum*, Jan 6–10, Orlando.
- How JP, Fraser C, Kulling KC, Bertuccelli LF, Toupet O, Brunet L, Bachrach A, Roy N. 2009. Increasing autonomy of UAVs: Decentralized CSAT mission management algorithm. *IEEE Robotics and Automation* 16(2):43–51.
- Humphreys CJ, Cobb RG, Jacques DR, Reeger JA. 2015. Optimal mission paths for the uninhabited loyal wingman. *16th AIAA/ISSMO Multidisciplinary Analysis and Optimization Conf*, Jun 22–26, Dallas.
- Humphreys CJ, Cobb RG, Jacques DR, Reeger JA. 2017. Dynamic re-plan of the loyal wingman optimal control problem. *AIAA Guidance, Navigation, and Control Conf*, Jan 9–13, Grapevine TX.
- James DL, Welsh MA III. 2014. United States Air Force RPA Vector: Vision and Enabling Concepts 2013-2038. Washington: United States Air Force.
- Johnson E, Kannan S. 2005. Adaptive trajectory control for autonomous helicopters. *Journal of Guidance, Control, and Dynamics* 28(3):524–38.
- Katz G, Barrett C, Dill DL, Julian K, Kochenderfer MJ. 2017. Reluplex: An efficient SMT solver for verifying deep neural networks. *arXiv* 1702.01135.
- Knight W. 2017. The dark secret at the heart of AI. *MIT Technology Review*, Apr 11.
- Kousik S, Vaskov S, Bu F, Roberson MJ, Vasudevan R. 2018. Bridging the gap between safety and real-time performance in receding-horizon trajectory design for mobile robots. *arXiv* 1809.06746.
- Liu J, Gardi A, Ramasamy S, Lim Y. 2016. Cognitive pilot-aircraft interface for single-pilot operations. *Knowledge-Based Systems* 112:37–53.

- Lyons JB, Koltai KS, Ho NT, Johnson WB, Smith DE, Shively RJ. 2016. Engineering trust in complex automated systems. *Ergonomics in Design* 24(1):13–17.
- Masiello TJ. 2013. Air Force Research Laboratory Autonomy Science and Technology Strategy (88AWB-2013-5023). Washington: US Air Force.
- Mitchell I, Bayen A, Tomlin C. 2005. A time-dependent Hamilton-Jacobi formulation of reachable sets for continuous dynamic games. *IEEE Transactions on Automatic Control* 50(7):947–57.
- Mizokami K. 2019. China's loyal wingman drone flies alongside manned fighters. *Popular Mechanics*, Aug 31.
- NRC [National Research Council]. 2014. *Autonomy Research for Civil Aviation: Toward a New Era of Flight*. Washington: National Academies Press.
- Overholt J, Kearns K. 2014. Transcript, Air Force Research Laboratory Autonomy Science & Technology Strategy Presentation, Apr 8. Online at https://defenseinnovationmarketplace.dtic.mil/wp-content/uploads/2018/02/AFRL_AutonomyPart2.pdf.
- Pittaway N. 2019. Boeing unveils loyal wingman drone. *Defense News*, Feb 27.
- Prevot T, Rios J, Kopardekar P, Robinson JE III, Johnson M, Jung J. 2016. UAS traffic management (UTM) concept of operations to safely enable low altitude flight operations. *AIAA Aviation Technology, Integration, and Operations Conf*, Jun 13–17, Washington.
- Rubies-Royo V, Calandra R, Stipanovic DM, Tomlin C. 2020. Fast neural network verification via shadow prices. *arXiv* 1902.07247.
- Schmid D, Stanton NA. 2019. Progressing toward airliners' reduced-crew operations: A systematic literature review. *International Journal of Aerospace Psychology* 30(1-2).
- Schmid D, Stanton NA. 2020. Considering single-piloted airliners for different flight durations: An issue of fatigue management. *Advances in Intelligent Systems and Computing* 964:683–94.
- Schouwenaars T, Valenti M, Feron E, How J. 2005. Implementation and flight test results of MILP-based UAV guidance. *IEEE Aerospace Conf*, Mar 5–12, Big Sky MT.
- Sha L. 2001. Using simplicity to control complexity. *IEEE Software* 18(4):20–28.
- Sharp C, Shakernia O, Sastry SS. 2001. A vision system for landing an unmanned aerial vehicle. *IEEE Internatl Conf on Robotics and Automation*, May 21–26, Seoul.
- Singh G, Gehr T, Mirman M, Püschel M, Vechev M. 2018. Fast and effective robustness certification. *Conf on Neural Information Processing Systems*, Dec 3–8, Montreal.
- Teo R, Jang JS, Tomlin CJ. 2005. Automated multiple UAV flight: The Stanford Dragonfly UAV program. *Proceedings, IEEE Conf on Decision and Control* 4:4268–73.
- USAF Chief Scientist. 2010. *Report on Technology Horizons: A Vision for Air Force Science & Technology During 2010-2030*. Technical Report AF/ST-TR-10-01-PR. Washington: US Air Force.
- Wang N, Pynadath DV, Hill SG. 2015. Building trust in a human-robot team with automatically generated explanations. *Interservice/Industry Training, Simulation and Education Conf*, Nov 30–Dec 4, Orlando.
- Wang S, Pei K, Whitehouse J, Yang J, Jana S. 2018. Efficient formal safety analysis of neural networks. *Conf on Neural Information Processing Systems*, Dec 3–8, Montreal.
- Winnefeld JA Jr, Kendall F. 2011. *Unmanned Systems Integrated Roadmap FY2011-2036*. Washington: US Department of Defense.
- Winnefeld JA Jr, Kendall F. 2013. *Unmanned Systems Integrated Roadmap FY2013-2038*. Washington: US Department of Defense.
- Zacharias GL. 2019. *Autonomous Horizons: The Way Forward*. Maxwell AFB AL: Air University Press.
- Zhang H, Weng TW, Chen PY, Hsieh J, Daniel L. 2018. Efficient neural network robustness certification with general activation functions. *Conf on Neural Information Processing Systems*, Dec 3–8, Montreal.
- Zhu S, Chen B, Chen Z, Yang P. 2019. Asymptotically optimal one- and two-sample testing with kernels. *arXiv* 1908.10037.

Hypersonic flight may one day enable same-day round-trip global travel.

Flying at the Edge of Space and Beyond: The Opportunities and Challenges of Hypersonic Flight



Kevin Bowcutt (NAE) is principal senior technical fellow and chief scientist of hypersonics for the Boeing Company.

Kevin G. Bowcutt

The primary benefit of hypersonic flight is extreme speed, whether to engage a time-critical or well-defended military threat, travel between global cities in a couple of hours, or achieve Earth orbit.

Hypersonic Flight and How It Is Achieved

Although the definition of supersonic speed is unambiguous—flying faster than the speed of sound—the beginning of hypersonic flight has no clear boundary. Mach 5 is generally accepted as the transition point from supersonic to hypersonic flow, but it is less clearly delineated by a speed boundary than a thermal boundary. Air passing over a vehicle traveling at hypersonic speeds becomes hot enough from shock compression and viscous dissipation to change its thermodynamic and chemical nature. The onset of these changes depends on several variables, including vehicle geometry.

Historically, beginning with rocket flight experiments and the X-15 rocket-plane (1959), hypersonic speed was attained with rocket propulsion, having no other options. But low fuel efficiency limits the practical use of rockets to propel airplanes over long distances. Because of the large fraction of propellant rocket-powered vehicles must carry (typically about 90 percent), little mass margin remains to accommodate design features and technology needed for the level of robustness and safety required by commercial airplanes.

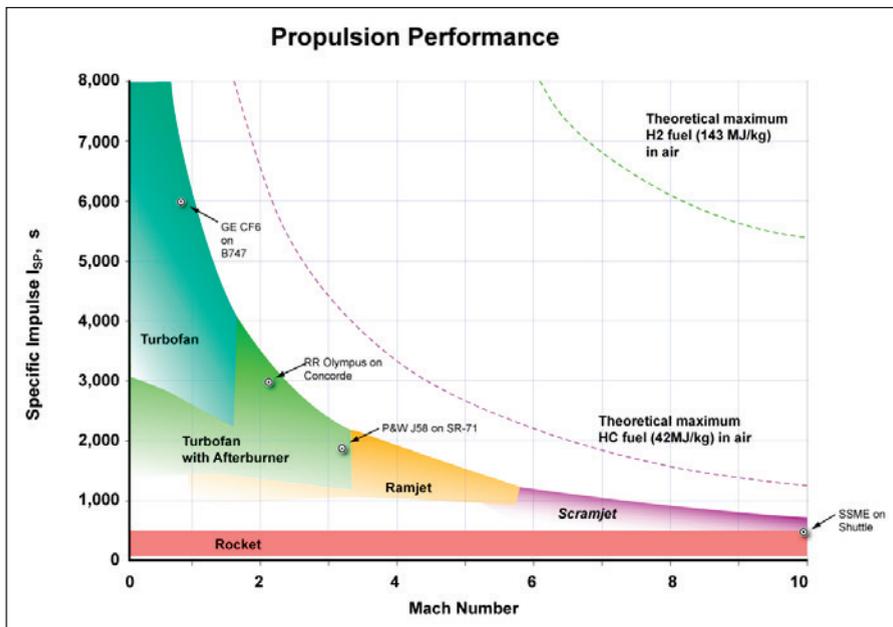


FIGURE 1 The fuel efficiency of air-breathing engines, measured by a quantity called specific impulse, can be substantially higher than for rocket engines, but decreases with flight speed (Mach number), as shown.

Unlike rockets, hypersonic air-breathing engines, such as the ramjet or supersonic combustion ramjet (scramjet), can make long-range hypersonic travel practical. The primary benefit of air-breathing engines is their relatively high fuel efficiency compared to rockets, measured in terms of a propulsion performance parameter called specific impulse (I_{sp}), which is engine thrust divided by propellant weight flow rate.

Figure 1 illustrates the fuel efficiency benefit of air-breathing engines (e.g., J58 on the SR-71) compared to rocket engines (e.g., SSME on the Space Shuttle) for hydrocarbon (kerosene-type) fuels. Lower I_{sp} levels for rockets are the result of their having to consume carried oxidizer as well as fuel, increasing the propellant weight flow rate in the denominator of the I_{sp} equation. Although air-breathing engines generally achieve higher I_{sp} than rockets, air-breathing I_{sp} decays with Mach number, as shown in figure 1. This trend is the result of air pressure rise from combustion heating, which is the source of thrust; as the air pressure rise decreases with speed, the thrust also decreases.

One of the greatest challenges to hypersonic flight is the availability of a propulsion system to efficiently accelerate vehicles from rest to hypersonic speed and then cruise at that speed. Due to thermal limits of materials and air itself, there is no single air-breathing engine type capable of doing this.

For example, above about Mach 3 to 4, the temperature of turbofan engine components will exceed material limits. This limit can be avoided by using a ramjet engine that has no turbomachinery components. But ramjets cannot operate from rest. They also are thermally limited because they slow down air from supersonic to subsonic speed through the action of shock waves, heating and pressurizing the air to exponentially higher levels with increasing speed.

At speed above about Mach 5 to 6, the air temperature becomes too high for efficient combustion for chemistry reasons. The ramjet flow temperature limit can be avoided by reducing the strength of inlet shock waves to maintain

supersonic flow in the combustor, creating a scramjet. Multiple engine types (e.g., rockets, turbofans, ramjets, and scramjets) must therefore be used or integrated in combined cycles (in one of myriad possible ways) to enable hypersonic flight.

As depicted in figure 2, scramjets are simple devices in principle—just shaped ducts with fuel injectors—but very challenging to properly design in practice. They must efficiently slow and compress air through the action of shock waves, then mix and burn fuel in a supersonic airstream in about a millisecond at relatively low air pressure but high air temperature.

Most scramjets are actually so-called dual-mode scramjets (or dual-mode ramjets), which operate as ramjets up to about Mach 6, with combustion occurring in air traveling slower than the speed of sound (i.e., subsonic flow), and thereafter as scramjets with combustion occurring in a supersonic air stream.

The Need for Speed

With the advent and explosive growth of information technology, the speed of communications and business has dramatically accelerated over the past three decades. In contrast, except for extremely limited Mach 2 Concorde service from 1976 until 2003, the speed of transportation hasn't risen much above eight-tenths the speed of sound since the beginning of the

jet age in 1958 with the introduction of the Boeing 707. This speed-of-life disparity has produced a demand for higher-speed air travel, therefore companies such as Aerion (with Boeing support) and Boom are developing a supersonic business jet and a supersonic airliner, respectively, and Boeing, the Spaceship Company, and Hermeus (along with organizations in Europe and Japan) are exploring design concepts for hypersonic passenger airplanes.

Figure 3 plots flight time saving as a function of cruise speed, depicted as the fraction of time a subsonic airliner takes to travel 5,000 nautical miles (nmi), approximately the distance from Los Angeles to Tokyo, accounting for the time and distance needed to accelerate and climb to cruise speed and altitude, and then to decelerate and descend to landing. As is evident from the plot, increased cruise speed has a dramatic impact on time saving until about Mach 5, beyond which time saving rapidly diminishes. One source of this asymptotic time-saving behavior is the longer time and distance required to accelerate and decelerate as cruise speed increases, reducing the time spent cruising. At Mach 10 cruise speed, the length of the cruise leg is almost zero. If aircraft range could be increased substantially, higher speed would produce measurable time saving.

When travel speed is fast enough, making transit time short enough, round-trip international travel can be accomplished in a single day, saving days, not just hours. There is tremendous value in this revolutionary level of time saving for some of the flying public.

Boeing is designing a Mach 5 passenger airplane to explore the market potential, and the design and technology requirements, of a future hypersonic commercial airplane. The airplane is being designed for a trans-

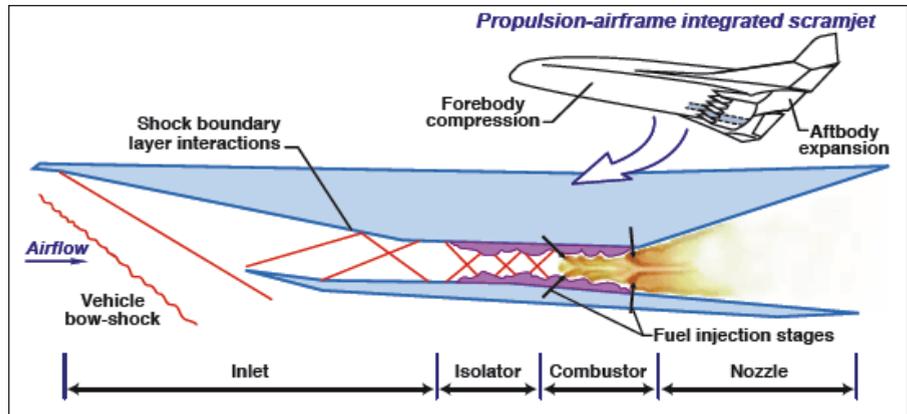


FIGURE 2 A scramjet is basically a shaped flow duct with components that include an air inlet, an isolator (that keeps combustion pressure from moving forward into the inlet), a combustor (where fuel is injected, mixed, and burned with air), and an exhaust nozzle. Scramjets must be highly integrated with the airframes they propel to achieve high performance. Source: NASA Langley website.

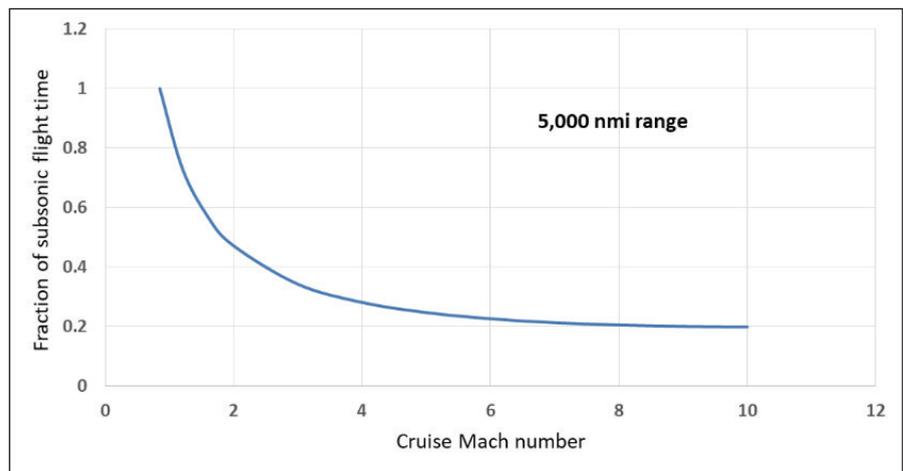


FIGURE 3 At hypersonic speed, the time saved flying between countries can make international day trips possible, but it diminishes quickly beyond about Mach 5 for practical travel distances. nmi = nautical mile.

Pacific range of 5,000 nmi and sized to carry between 10 and 200 passengers. An artist's concept of the airplane shows some of its major design features (figure 4).

With a top speed of Mach 5, too slow for a scramjet, the airplane would be powered by a turbo-ramjet engine, a turbofan engine for low-speed thrust integrated with ramjet for high-speed thrust. The engines would burn a sustainable hydrocarbon fuel derived from biomatter to mitigate carbon emissions (more on this below). The fuel would also have so-called endothermic properties, allowing it to absorb large amounts of heat to cool air flow and airplane systems. It is anticipated that such a hypersonic airliner could be ready for market in 15 to 20 years.

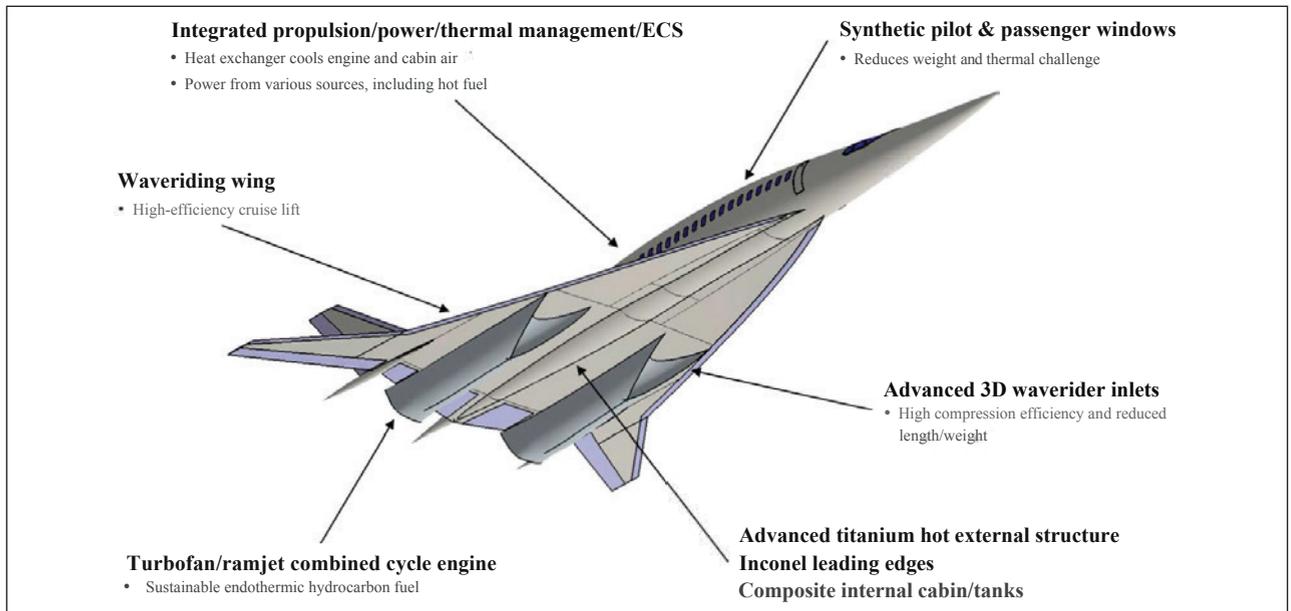


FIGURE 4 Boeing hypersonic airliner concept using many design and technology advances to enable Mach 5 cruise flight. ECS = environmental control system.

Technology Advances That Have Enabled Air-Breathing Hypersonic Flight

Three technology advances over the past three decades have enabled hypersonic air-breathing flight to become a reality: maturation of dual-mode scramjet engines through ground and flight testing, enhanced high-temperature metal and ceramic materials, and dramatically faster and higher-fidelity computational simulation capabilities for fluid dynamics (applied to aerodynamics and propulsion), materials, structures, and multidisciplinary system design optimization. The first two of these are described in the following sections; for a discussion of computational simulation capabilities, see Candler et al. (2015).

Maturation of Dual-Mode Scramjet Engines Through Ground and Flight Testing

The idea of an engine burning fuel in a supersonic airstream—i.e., the scramjet—was first reported by engineers at the National Advisory Committee for Aeronautics in 1958 (Weber and Mackay 1958). From the 1960s through the 1990s, significant scramjet research, design, and ground testing took place in the United States and several other countries, including the Soviet Union (Russia), France, Japan, and Australia. The greatest advances in scramjet technology development during this period were made with large investments from

the US National Aero-Space Plane (NASP) program (Heppenheimer 2007; Schweikart 1998).

Also in the 1990s, initial attempts were made by Russia, at first independently but later in partnership with France and then the United States, to flight test a scramjet combustor by attaching it to the nose of a rocket-propelled missile. Results from these flight tests were inconclusive in terms of achieving supersonic combustion. Then in 2002, the University of Queensland in Australia flew a scramjet combustor attached to the nose of a sounding rocket and confirmed supersonic combustion. But these tests were focused exclusively on testing supersonic combustion in flight and did not attempt to measure thrust, the key requirement of a propulsion system.

The most definitive initial demonstration of scramjet technology occurred in 2004, with NASA and industry partners, including Boeing, twice flying the X-43A (also called Hyper-X; figure 5)—a flight experiment spin-off from the NASP program that integrated a hydrogen-fueled scramjet on a lifting body airframe—at speeds of nearly Mach 7 and Mach 10. Because of the relatively low density of gaseous hydrogen only 10 seconds of scramjet data were collected, but this was enough to demonstrate for the first time in history that an airframe-integrated scramjet worked as theorized, almost 50 years after the idea of a scramjet was conceived. Not only did the scramjet successfully operate, it generated thrust greater



FIGURE 5 Left: The X-43A was the first vehicle powered by a scramjet engine, proving that the technology works as predicted. Right: The X-51A was the first vehicle powered by a lightweight scramjet that cooled its structure with hydrocarbon jet fuel. Sources: NASA (left), Boeing (right).

than drag at Mach 7 and approximately equal to drag at Mach 10, very closely matching preflight engine analysis predictions and verifying the propulsion efficiency potential of scramjets.

The next step in the advancement of scramjet technology occurred in 2013 with the final of four flight tests of a hydrocarbon-fueled scramjet on the X-51A (also called the Scramjet Engine Demonstrator, shown in figure 5) by the US Air Force Research Laboratory with industry partners, including Boeing. After rocket boost, the X-51A operated on dual-mode scramjet power for 209 seconds before running out of fuel, accelerating from Mach 4.8 to 5.1. A key difference between the X-43A and X-51A was the latter's lightweight airframe and scramjet, with fuel used to cool the scramjet, whereas the former had a heavy uncooled solid copper scramjet engine and heavy airframe, more akin to what would be tested in a wind tunnel. Since the X-43A and X-51A flights, other countries have flown scramjets too.

Enhanced High-Temperature Metal and Ceramic Materials

Vehicles that fly at the lower end of the hypersonic speed range (Mach 4 to 6) can be made primarily of high-temperature metals such as advanced titanium and nickel alloys and superalloys. These materials are structurally functional in the temperature range from about 1000°F to 2000°F (540°C to 1080°C), although nickel-based alloys are on the heavy side for airframe structure applications. Current research is focused on increasing the temperature capability of lightweight titanium alloys.

Beyond about Mach 6 is the realm of carbon- and ceramic-based composite materials, typically fibers made of carbon, silicon-carbide, alumina, or silica in a

matrix of one of these materials. The temperature capability of these carbon- and ceramic-matrix-composite materials extends up to 3100°F (1700°C) for multiuse and up to 3600°F (2000°C) for single use.

Why a Hypersonic Airliner Now?

One might ask, if the supersonic Concorde was not economically successful, what is different today that would allow a hypersonic airliner to be successful? Much has changed since Concorde was developed, resulting in technical and economic factors that could make hypersonic travel practical today.

Technological Advances

Technology has advanced significantly across many fronts over the past 60 years to support the design of a hypersonic airplane:

- Sophisticated computer-based modeling and simulation capabilities allow accurate analysis and optimization of aerodynamics, propulsion, materials, structures, and flight controls.
- The entire airplane system can be optimized, concurrently accounting for all of these disciplines, using a process called multidisciplinary design optimization.
- Advances in metallic, ceramic, and composite materials allow airplane and engine structures to be lighter and more durable, with higher temperature capability, as described above.
- Also available are more efficient and lighter-weight jet engines, advanced thermal management technology, lighter and more compact electronics, and lightweight high-power electric systems such as motors and actuators.

Global Economic Growth

The world economy is growing at an exponential rate, producing a 250 percent increase in real GDP per capita globally since 1970 (Bolt et al. 2018). In direct correlation, air transport demand consistently grows with progress in real GDP per capita (Boeing 2019). It follows that the demand for premium air travel will increase in proportion to overall air travel demand.

The total cost of travel can be thought of in terms of money, time, and experience. Monetary costs are often traded against improvements in the time-based or experiential costs of travel. Think of direct travel as opposed to indirect routings with awkward connections, or the demand for comfortable business and first-class seating as opposed to economy. Hypersonic travel will not be the least expensive option in the future market, but it is a different way to address premium travel demand, with money traded for major improvements in time as opposed to money traded for comfort (i.e., for first or business class travel).

Hypersonic travel is a different way to address premium travel demand, with money traded for major gains in time.

In today's world, hypersonic travel cannot be bought at any price. In tomorrow's world, hypersonic transport may be available at prices competitive with first-class airfares, addressing a well-established market for premium travel with a compelling and unique offering, provided that other experiential costs—safety, comfort, and greenhouse gas emissions—do not also rise.

Hypersonic Airliner Environmental Challenges and Policy Hurdles

CO₂ Emissions

Lifetime CO₂ emissions for a hypersonic airplane are a strong function of the amount of fuel burned and a weaker function (<1 percent) of the energy and materials used to fabricate, assemble, maintain, and dispose of the airplane. How the fuel is created can make

a large difference as well. Fortunately, biofuel versions of hydrocarbon fuels can provide significant environmental benefits because CO₂-absorbing biomass is used as feedstock to create the fuel. It is expected that this fuel would reduce lifecycle CO₂ emissions by up to 70 percent.

Using current performance assumptions, calculations show that CO₂ emissions per passenger mile for a hypersonic airliner will be comparable to those of a supersonic airliner, but still much higher than for a conventional subsonic transport because of the increased fuel use needed to fly at supersonic or hypersonic speed. However, a passenger on a hypersonic airliner using 100 percent biofuel will have a comparable CO₂ footprint per passenger mile to someone flying first class in a subsonic airliner that uses conventional Jet A fuel. While it is true that using 100 percent biofuel on conventional subsonic aircraft would give it a CO₂ advantage, the relatively small fraction of passengers anticipated to fly on hypersonic airliners will largely mitigate the effects of this difference.

Biofuels are more expensive than traditional petroleum-based fuels, especially in the relatively small quantities now produced (<1 percent of current jet fuel supply). This actually presents an opportunity for supersonic and hypersonic airplanes as their passengers are less likely to be sensitive to ticket price, hence fuel price. In other words, they would be more likely to pay an additional premium to travel in a more eco-friendly manner, and in so doing spur the demand for biofuel, driving down the cost for all users. Existing aircraft, with legacy fuel and engine systems, are generally limited to 50 percent biofuel blends; new aircraft, such as a hypersonic transport with new or modified engines, can be designed to use 100 percent biofuels.

The effects of emissions on stratospheric ozone from a hypersonic airplane flying at about 100,000 ft. altitude have not been fully evaluated by the atmospheric science community. NO_x emissions are expected to lead to some level of ozone depletion, but the amount will depend on cruise altitude, the quantity of NO_x emitted from engines, and fleet fuel use. Water vapor emissions from a hypersonic airplane will accumulate in the stratosphere, potentially affecting ozone as well. Moreover, CO₂ and water vapor emissions are both greenhouse gases, but the climate effects of these emissions in the stratosphere have yet to be evaluated.

Atmospheric chemistry models are starting to be used to evaluate the effects of these emissions on the

atmosphere for airplanes cruising at altitudes up to 110,000 ft. When available, the results of these assessments can be used to guide policymakers and technology developers on hypersonic airplane requirements.

Sonic Boom

As with supersonic aircraft, sonic boom is a challenge for hypersonic aircraft. One might expect it to be worse for a hypersonic aircraft because of its higher speed, but in fact several high-altitude effects may reduce sonic boom more than Mach number effects increase it.

Although hypersonic airliner flight may initially be limited to overwater and unpopulated overland routes, airplane design techniques and technology being developed in NASA's supersonic boom reduction research program may eventually be applied to hypersonic airplane design to further mitigate sonic booms.

Trade-offs between the value of speed and the technological and environmental impacts of flying faster and higher suggest that there may be an optimum speed/altitude combination that retains the economic benefits of speed while minimizing the technological challenges of flying faster (which tend to increase by the square of Mach number) and the environmental effects of emissions and sonic boom.

Certification and Regulation

Some aspects of certifying hypersonic airplanes will be different than for subsonic or even supersonic airplanes:

- the hot structure and associated thermal protection and management systems needed to maintain a cool environment for the cabin and systems;
- unique systems and approaches to prevent cabin decompression, which is not permissible at the altitudes hypersonic airplanes fly;
- a synthetic vision system needed by pilots because the unique airplane geometry required for acceptable aerodynamic performance prevents adequate optical views; and
- higher landing and takeoff noise that are a natural consequence of having to use lower-bypass turbofan engines to achieve acceptable engine performance at supersonic speed.

The first three will require development of certification approaches that ensure their safety; the last may require a change in noise regulations until noise reduction technology is advanced for supersonic low-

bypass engines. NASA is innovating a certifiable pilot synthetic vision system for the X-59 Quiet SuperSonic Technology (QueSST) experimental aircraft being developed by Lockheed Martin, giving this system a head start for certified hypersonic airplane applications (Hernandez 2019).

Several high-altitude effects may reduce sonic boom more than Mach number effects increase it.

An additional consideration for hypersonic airplanes will be integrating them into national airspace, as they will require special handling during airport departure and return to operate within the traffic patterns of slower-moving aircraft. For example, they will have to fly within specific corridors during ascent to safely accelerate to speed and slow down sufficiently far from airports on approach. During ascent and descent they will also have to manage flight trajectory to focus sonic booms, which are stronger during acceleration and deceleration, in acceptable directions. The integration of supersonic airplanes into subsonic air traffic patterns has been a subject of study for many years (e.g., Underwood 2017).

Exciting Possibilities Lie Ahead with Hypersonic Flight

Imagine in the near future being able to board a hypersonic airplane and jet across the ocean in 2 to 3 hours, returning home the same day if desired. Or, in the more distant future, hopping on a two-stage spaceplane, with a Mach 5 airplane first stage and a second stage propelled by an integrated scramjet-rocket engine, to fly safely and affordably to an orbital hub on your way to the Moon or Mars. These futures are being made possible by advances in technology for hypersonic flight that started 60 years ago and are being dramatically accelerated today.

This is an exciting time with the development of numerous aerospace innovations that will transform how people and material move around the globe. Hypersonic flight will effectively shrink the globe in terms of the time required for physical interaction, an undying element of human need and experience.

Acknowledgments

Thanks for valuable inputs from Boeing employees David Franson, Marty Bradley, Steven Baughcum, Todd Magee, David Lazzara, and Hao Shen.

References

- Boeing. 2019. Commercial Market Outlook 2019–2038. Seattle.
- Bolt J, Inklaar R, de Jong H, van Zanden J. 2018. Rebasing ‘Maddison’: New income comparisons and the shape of long-run economic development. Maddison Project Working Paper 10. Groningen Growth and Development Centre, University of Groningen. Available at <https://ourworldindata.org/economic-growth>.
- Candler GV, Subbaredd PK, Brock JM. 2015. Advances in computational fluid dynamics methods for hypersonic flows. *Journal of Spacecraft and Rockets* 52(1):17–28.
- Heppenheimer TA. 2007. Facing the Heat Barrier: A History of Hypersonics (NASA SP-2007-4232). Washington: National Aeronautics and Space Administration.
- Hernandez JC. 2019. Testing of X-59 virtual forward window successful. NASA, Aug 26.
- Schweikart L. 1998. The Hypersonic Revolution: Case Studies in the History of Hypersonic Technology, Vol III – The Quest for the Orbital Jet: The National Aero-Space Plane Program (1983-1995). Washington: Bolling AFB.
- Underwood MC. 2017. Concept of Operations for Integrating Commercial Supersonic Transport Aircraft into the National Airspace System (NASA/TP–2017-219796). Hampton VA: NASA Langley Research Center.
- Weber RJ, Mackay JS. 1958. An Analysis of Ramjet Engines Using Supersonic Combustion (NACA-TN-4386). Cleveland: Lewis Flight Propulsion Lab.

Challenge humankind to do something extraordinary, offer a handsome cash incentive, and people may surprise you.

Aerospace Prizes Inspire the Five I's of Success: Imagination, Invention, Innovation, Investment, and Impact



Darryll Pines (NAE) is the Glenn L. Martin Professor of Aerospace Engineering, A. James Clark School of Engineering, and incoming president, University of Maryland, College Park.

Darryll J. Pines

The United States' economic growth and competitiveness depend on the capacity to innovate. Innovation and entrepreneurship in aerospace have historically kept the United States at the forefront of technology advances and spurred economic growth, creating new industries such as commercial transportation of cargo and humans, uninhabited aerial systems for civilian and military missions, and more recently private commercial space travel and exploration.

A key catalyst for aerospace innovation and entrepreneurship has been aerospace prizes and competitions that inspire the five I's: imagination, invention, innovation, investment, and impact. The articulation of what might be considered unreachable goals and objectives inspires creativity, tolerance for risk, and the spirit of competition.

Introduction

In the United States, since the Wright brothers' first controlled, powered flight in 1903 aerospace prizes have played a pivotal role to accelerate the growth and development of the aerospace industry. They have challenged the state of the art, attracted new talent to the field, and inspired technologists, aviators, and entrepreneurs to make revolutionary advances in aerodynamics, lightweight high-strength and reliable structures, high thrust-

to-weight propulsion, and robust electronics for navigation and control of vehicles that fly in the air or in space.

Properly defined prizes/challenges (e.g., with clear metrics) can have the following positive effects:

- disruptive advances in the state of art of a particular technology or in fundamental understanding of physical phenomena;
- new inventions and breakthrough solutions to existing goals;
- interaction and collaboration among diverse groups to solve a complex problem;
- simultaneous advancement in multiple technologies (e.g., propulsion, structural design, and aerodynamics);
- innovation and entrepreneurship leading to new processes and companies, and in some cases a new industry; and
- change in culture as a creative mindset becomes a foundational part of an institution.

Three Influential Aerospace Prizes

Over 50 major prizes were offered in aeronautics before 1929, including for speed, distance, and transcontinental and transoceanic flight. To illustrate the effect of such challenges, three prizes that have inspired innovation and entrepreneurship and advanced aerospace technology and commercialization are reviewed here:

- The Orteig Prize for the first transatlantic flight from New York to Paris
- The Kremer Prizes for human-powered flight
- The Ansari XPRIZE for the first private firm to carry a human into space.

The Orteig Prize for Transatlantic Flight

Established: 1919, claimed: 1927; award: \$25,000 (\$1M in current dollars)

In 1919 Raymond Orteig, a New York City hotel owner, offered a prize of \$25,000 for the first nonstop flight between New York and Paris. Unfortunately, the first aviators to go for the prize paid with their lives. By the mid-1920s aviation had sufficiently advanced to make such a flight possible, and on May 21, 1927, Charles A. Lindbergh completed the first solo non-

stop transatlantic flight, flying his Ryan NYP *Spirit of St. Louis* 5,810 kilometers (3,610 miles) from New York to Paris in 33½ hours. When he landed at le Bourget Field, he won the \$25,000 prize and became a world hero whose historic flight inspired generations.

Some of the enabling technologies that contributed to Lindbergh's success were

- advances in subsonic aerodynamics and aircraft design;
- the introduction of reliable, high power-to-weight piston engines; and
- the development of all-metal airliners (a portion of Lindbergh's aircraft was metal), which could carry enough revenue passengers to be profitable.

Additional factors that contributed to aviation success during this time were

- an influx of capital from a booming stock market—over 16 times the prize amount was invested in efforts to win the Orteig Prize;
- the start of air mail routes in the United States, which subsidized new airline service;
- the first lighted airway;
- airplane service and cargo flights to the Caribbean; and
- movie reels and newspaper-funded publicity.

The Dow Jones average jumped following Lindbergh's historic transatlantic flight in 1927, and the field of aviation saw significant growth throughout the 1930s as the country found new uses for aircraft and rotorcraft.

The Kremer Prize for Human-Powered Flight

Established: 1959, claimed: 1977; award: £50,000

Aviation enthusiasts long sought to realize the human-powered flight dreams of Leonardo da Vinci (Barks 2009). Were the artist's 15th century designs achievable—was it possible for a human to power an aircraft over a long distance? Early attempts demonstrated that a human could indeed achieve liftoff, albeit for a very short period of time.

To accelerate advances in human-powered flight (Reay 1977), British industrialist Henry Kremer announced in 1959 the establishment of the Kremer Prize of £5,000 (increased to £50,000 in 1973) with the following aircraft requirements:

- The machine must be heavier than air.
- The use of lighter-than-air gases was prohibited.
- The machine must be powered and controlled by the crew over the entire flight.
- No device for storing energy either for takeoff or for use in flight was permitted.
- No part of the machine should be jettisoned during any part of flight including takeoff.

The competition was initially open only to citizens of the British Commonwealth, later to people everywhere.

Paul MacCready (NAE) of the United States and his group of engineers and colleagues took the first Kremer prize in 1977, for a figure eight flight with the Gossamer Condor, a double-skinned airfoil with a large wing and a pilot nacelle. It was flown by cyclist and hang-glider Bryan Allen who, on August 23, 1977, completed the 1.6-mile course designated by the Royal Aeronautical Society, at Minter Field in Shafter, California.

MacCready and his team then set their sights on Kremer's second prize, which called for flying a human-powered aircraft across the English Channel. On June 12, 1979, the 70 lb Gossamer Albatross became the first fully human-powered aircraft to do so (figure 1), completing the 26-mile flight in 2:49 hours.

Following the inspiring work of MacCready, another group emerged to extend human-powered flight to even greater distances and longer duration. The group of MIT faculty, students, and a few alumni met in 1984 to discuss their next challenge after successful flights of their Monarch human-powered aircraft. They decided to develop a vehicle that could complete the mythical flight of Daedalus between the Greek islands of Crete and Santorini. The team, led by John Langford (NAE) with support from MIT aerodynamics professor Mark Drela (NAE), involved 40-plus MIT students, engineers, and alumni.¹ The team's collective dreams were achieved April 23, 1988, by a vehicle called Daedalus piloted by Greek cycling champion Kanellos Kanellopoulos, who flew 71.5 mi (115.11 km) in 3:54 hours from Iraklion on Crete to Santorini. The flight still holds official world records in distance and duration for human-powered aircraft.

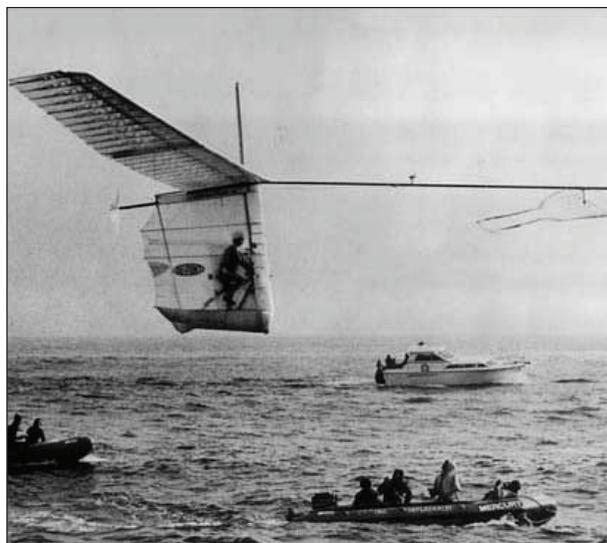


FIGURE 1 The human-powered Gossamer Albatross flying across the English Channel, June 12, 1979. Courtesy of AV-AeroVironment.

Enabling technology and process innovations from the development of successful human-powered aircraft include

- high strength-to-weight composite structures and design,
- low Reynolds number aerodynamics at low Mach number,
- integrated system design of high-aspect-ratio winged vehicles, and
- advances in human performance and training to yield high power-to-weight ratios and low overall weight.

These successful flights of human-powered fixed-wing aircraft inspired an entire generation of aerospace engineers and scientists, even hobbyists, all seeking to advance the field of human-powered flight. Advances led to the emergence of high-altitude long-endurance uninhabited aerial vehicles (UAVs) with power provided by piston engines, batteries, or energy harvested from the sun—and the establishment of two new UAV firms, founded by Kremer Prize winners MacCready and Langford (table 1). Today these two aerospace firms develop innovative UAV designs for a variety of customers and together employ over 1,000 people.

¹ During this time I was a graduate student at MIT and my office mate, Siegfried Zerweckh, was a structural engineer on the Daedalus project.

TABLE 1 UAV firms founded by Kremer Prize winners

| Company | High-altitude vehicles | Year of test flights | Headquarters | Number of employees | Year founded |
|---|---|----------------------|--------------|---------------------|--|
| AeroVironment Founder: Paul MacCready |   Pathfinder Helios | 1998, 2001 | Monrovia, CA | 700 | 1971 |
| Aurora Flight Sciences Founder: John Langford |  Theseus   Perseus B Vulture concept | 1996–99 | Manassas, VA | ~450 | 1989 (sold in 2018 to Boeing Corporation) |



FIGURE 2 SpaceShipOne (on top), winner of the Ansari XPRIZE in 2004. Reprinted with permission from Belfiore (2007).

The Ansari XPRIZE for Commercial Space Flight

Established: 1996, claimed: 2004; award: \$10 million

The XPRIZE was proposed in 1995 by Peter Diamandis (Diamandis and Kotler 2012) and established in May 1996 with funding from individuals, foundations, and companies. It was renamed in May 2004 after a multimillion-dollar donation from entrepreneurs Anousheh Ansari and Amir Ansari.

The prize “was designed to lower the risk and cost of going to space by incentivizing the creation of a reliable, reusable, privately financed, manned spaceship that finally made private space travel commercially viable.”²

From the 26 teams that officially entered the competition, the prize was won October 4, 2004—the 47th anniversary of the Sputnik 1 launch—by the Tier One project designed by aerospace pioneer Burt Rutan (NAE; founder

of Scaled Composites) and financed by Microsoft cofounder Paul Allen (NAE), using the experimental SpaceShipOne (figure 2). It is estimated that more than \$100 million was invested in technologies in pursuit of the prize.

The high visibility and success of the Ansari XPRIZE, and the creation of new prizes with the retirement of NASA’s space

shuttle and the agency’s shift to using the commercial sector for space transportation, led to the emergence of a number of space companies—Virgin Galactic, SpaceX, Bigelow Aerospace, Blue Origin, and Rocket Lab, among others. They support commercial demand for launch services, satellite development, space science and education, space marketing, and interest in space tourism.

The prize and its timing generated innovation and entrepreneurship among aerospace pioneers such as SpaceX founder and CEO Elon Musk. SpaceX, founded in 2002, is a successful launch services provider that has proven it is possible to launch reusable rockets that can deliver payloads to low and medium Earth orbits and at an affordable price.

SpaceX’s firsts include (i) the first privately funded, liquid-propellant rocket (Falcon 1) to reach orbit, in 2008; (ii) the first privately funded company to successfully launch, orbit, and recover a spacecraft (Dragon),

² <https://www.xprize.org/prizes/ansari>

in 2010; and (iii) the first private company to send a spacecraft (Dragon) to the International Space Station, in 2012. In addition, in December 2015 SpaceX successfully returned a first stage to the launch site and accomplished an autonomously controlled vertical landing, the first by a rocket on an orbital trajectory.

Aerospace Prizes Yet to Be Claimed

While the field of aerospace has seen significant advances as a result of the establishment of prizes and competitions with clear metrics that don't violate the laws of physics, there are a number of aerospace prizes that have yet to be claimed (table 2).

New Aerospace Prizes?

The aerospace engineering and business community should consider developing a few revolutionary prizes to inspire American innovation and entrepreneurship and possibly new industries. Some possibilities for new aerospace challenge competitions are briefly described below.

Asteroid Prize

There are two motivations for this prize, which might be offered in either or both of the following categories.

1. There is a need to inspire astronomers and enthusiasts to develop early warning methods and techniques to track and catalogue asteroids and meteorites that might collide with Earth. One option is to award a prize to an individual or team for detecting the smallest celestial body that will come within 12,500 km of hitting planet Earth within the next 50 years. This distance was chosen because many spacecraft assets (including GPS constellation) are in orbits of less than 12,500 km.
2. Asteroids and meteorites may be a rich source of new minerals and metals with special properties that are simply not seen in materials found on earth. A prize would be awarded to the first team to land a rover and spacecraft on a near-Earth asteroid and return scientific data about samples for evaluation. This prize could inspire future mining operations of asteroids for rare metals that may lead to enhanced uses of such materials on Earth.

All-Electric Vertical Takeoff and Landing Urban Air Mobility Prize

Urban air mobility (UAM) refers to urban transportation systems that move people by air; to accommodate

urban space constraints, such systems rely on vertical takeoff and landing. UAM systems are being developed to ease urban traffic congestion.

A UAM prize, similar to the DARPA Urban Challenge, would recognize the first team to develop an autonomous UAM vehicle that successfully navigates an urban environment to transport occupants 5 to 10 miles safely and reliably to a designated transportation hub.

Transport Aircraft Planform Prize

This prize would reward the subscale demonstration of a commercially viable new transport aircraft planform enabling a 10–20 percent increase in fuel efficiency. The aircraft might use, for example, blended wing-body, hybrid wing-body, or double-bubble concepts.

Space Power Prize

This prize would reward the demonstration of new space power concepts (e.g., nuclear) to revolutionize space power, propulsion, industry, and human habitation on the Moon or other planets.

Summary

Three historical aerospace prizes—Orteig, Kremer, and Ansari XPRIZE—contributed importantly to economic development, innovation, entrepreneurship, and the growth of the aerospace industry. The establishment of such prizes and their pursuit are part of aerospace culture, bringing out risk takers, explorers, innovators, and entrepreneurs and celebrating the quest of the human spirit to be free and untethered by Earth's gravity.

They demonstrate that properly defined aerospace competitions and prizes can have one or more of the following positive effects:

- inspire imagination, invention, innovation, investment, and impact;
- leverage external financial investment that is typically 5–10 times the actual prize value;
- accelerate advances in key enabling technology;
- bring together people of diverse disciplines and backgrounds to collaborate on solving a problem;
- lead to new industries that generate job creation and economic development;
- and finally, engage and galvanize the next generation of students who aspire to be aerospace pioneers and contribute to the field.

TABLE 2 Claimed/unclaimed aerospace prizes

| Aerospace prize/challenge (website) | Goal | Year est. | Award value | Source of funding/sponsor | Winner |
|--|--|-----------|----------------|---|--|
| AlphaPilot Innovation Challenge (https://www.lockheedmartin.com/en-us/news/events/ai-innovation-challenge.html) | Design AI to pilot drones through professional drone racing courses • AlphaPilot provides specially designed drones containing the latest GPU devices • No offloading of data permitted—teams must perform 100% edge computation | 2019 | \$1M | Lockheed Martin | Claimed, Dec 10, 2019: Team MAVLab of Delft University of Technology. |
| American Helicopter Society Sikorsky Prize (www.vtol.org/awards-and-contests/human-powered-helicopter/hph-rules) | Design a human-powered helicopter that can hover for at least 60 seconds at a height of 3 m within a 10 m by 10 m space | 1981 | \$250,000 | Sikorsky Aircraft Corporation/ American Helicopter Society Igor Sikorsky Prize | Claimed, Jul 11, 2013: AeroVelo (based in Toronto). |
| America Space Prize (www.space.com/375-50-million-prize-private-orbiting-spacecraft.html) | Transport a five-person crew into orbit for 60 days, twice, at altitude of 400 km | 2004 | \$50M | Bigelow Aerospace | Unclaimed. Prize expired in Jan 2010. |
| Cheap Access to Space (CATS) Prize (http://archive.spacefrontier.org/Projects/CatsPrize/) | Inexpensive commercial launch of payload into space | 1997 | \$250K | Anonymous donor/ Space Frontier Foundation | Unclaimed. Ended Nov 8, 2000. |
| GoFly Competition (https://goflyprize.com/) | Design, build, and fly a personal flying device that must be safe, quiet, ultracompact, near-VTOL, and capable of carrying a single person for a distance of 20 miles without refueling or recharging | 2018 | \$2M | Boeing Company | Unclaimed; competition still open after “final flyoff” Feb 29, 2020—no winner. |
| Google Lunar X Prize (www.googlelunarxprize.org/) | Land a robot on the surface of the Moon, travel 500 meters over the lunar surface, and send images and data back to Earth | 2007 | \$30M | Google | Unclaimed. Prize expired Mar 31, 2018. |
| N-Prize (www.n-prize.com/) | Launch a satellite weighing between 9.99 and 19.99 grams into Earth orbit, and track it for a minimum of nine orbits | 2008 | £9,999.99 | Paul Dear | Unclaimed. Closed following the death of Paul Dear Mar 11, 2020. |
| NASA’s Centennial Challenges (www.nasa.gov/directorates/spacetech/centennial_challenges/overview.html) | Four challenges: Sample Return Robot Challenge 3D Printed Habitat Challenge Mars Ascent Vehicle Prize CubeQuest Challenge | 2005 | Multiple >\$1M | US government/ NASA | Unclaimed. |

Prizes inspire and honor those who are successful at staring down the impossible and making it possible. As Robert F. Kennedy said, “Only those who dare to fail greatly can ever achieve greatly.”

References

- Bark J. 2009. *Journal of Inventions: Leonardo da Vinci*. San Diego: Silver Dolphin Books.
- Belfiore M. 2007. *Rocketeers: How a Visionary Band of Business Leaders, Engineers, and Pilots Is Boldly Privatizing Space*. New York: Smithsonian Books.
- Diamandis PH, Kotler S. 2012. *Abundance: The Future Is Better Than You Think*. New York: Free Press.
- Reay DA. 1977. *The History of Man-Powered Flight*. Oxford: Pergamon Press.

Commercial aviation is a complex industry that requires strong ethical decision-making skills to maintain safety.

EES Perspective

Ethical Decision Making and the Aviation Industry



Elizabeth Hoppe is an instructor in philosophy at Loyola University Chicago.

Elizabeth A. Hoppe

The discipline known as ethics concerns the study of what one ought to do. However, simply because a person knows which action is morally right does not necessarily mean s/he will actually do it. Time constraints, economic pressure, and human factors can all contribute to poor ethical decision making. In some industries ignoring what ought to be done has sometimes led to tragic results.

From questions of personal and corporate responsibility to impacts on the environment, ethical concerns are of vital importance in aviation. This column highlights two ethical theories that can aid in addressing such concerns. It then illustrates the application of ethics to the Boeing 737 MAX accidents, disease containment, and persistent contrails.

Two Relevant Ethical Theories

While ethical decision making is of paramount importance for any industry devoted to safety, deciding the best course of action is often fraught with difficulties. Often there is no clear-cut answer for how to act in a specific situation.

No single ethical theory can solve all moral dilemmas, but using ethical theory can be an important tool in addressing them. And qualitative

This column is produced in collaboration with the NAE's Center for Engineering Ethics and Society to bring attention to and prompt thinking about ethical and social dimensions of engineering practice.

ethical analysis can complement the rigorous quantitative risk assessment methods presented in this issue by B. John Garrick and Ali Mosleh (2020), especially given increasing reliance on autonomous systems.

Two prominent ethical theories that can be usefully applied in aviation are deontology and consequentialism.

Deontology, or Moral Duty

Deontology is associated with the works of Immanuel Kant (1724–1804), who based ethics on the concept of moral duty. He articulated a principle called the categorical imperative, which states that any personal rule or maxim that can apply universally to all rational beings becomes a moral law that is obligatory for everyone to follow.

But the categorical imperative is not always easy to apply, especially in cases where a conflict of moral duty may arise. For instance, Kant claims that both truth telling and keeping promises are moral laws. But promising to keep a secret, for example, may entail telling a lie, violating the duty of truth telling. Some critics also take issue with the lack of grey areas in Kantian ethics. Right is right and wrong is wrong, making deontology a rigid theory to apply in practice.

Consequentialism

Rather than create moral laws based on duty, consequentialism focuses on the end results of actions to determine right and wrong. Consequentialist ethics fits in well with issues such as environmental sustainability practices where the needs of the present must consider the needs of the future.

Utilitarianism

One of the important consequentialist theories is utilitarianism, which calculates which consequences will maximize happiness. Its approach is analogous to the economic concept of cost-benefit analysis. Instead of using monetary values to weigh both sides, utilitarianism calculates the amount of happiness or pleasure versus the pain that may result from an action. If the amount of pleasure gained outweighs any pain involved, then the action is morally right.

However, as with other ethical theories, consequentialism has drawbacks. In maximizing happiness, the ends justify the means. But should motives not play a role in determining whether an action is morally justified? Another problem is that the results may very well entail that some suffer for others to prosper. The

suffering of the few would be morally allowed under utilitarianism. Finally, by focusing only on end results, utilitarianism leaves out consideration of important factors such as a decision maker's character and/or motives.

Anticipatory Technology Ethics

Keeping in mind that no ethical theory can fit every circumstance, one form of consequentialism, anticipatory technology ethics, is especially important for science and technology as it deals specifically with the potential social consequences of emerging technologies. It can be defined as “the practice of using the design phase to reflect upon how a system or technology's affordances will impact their use and potential consequences” (Shilton 2015, p. 1). It has also been explained as “the study of ethical issues at the [research and development] (R&D) and introduction stage of technology development through anticipation of possible future devices, applications, and social consequences” (Brey 2012, p. 1).

No single ethical theory can solve all moral dilemmas, but using ethical theory can be an important tool in addressing them.

At the R&D stage ethical issues may be unknown since the technologies are not yet in use by society at large, but efforts to uncover potential ethical dilemmas at this stage can help prevent ethically undesirable outcomes. Futures studies are one way to determine possible ethical conflicts that may arise with new technologies under development (Brey 2012). But forecasting impacts can be uncertain, so this approach to ethics cannot cover all issues that may arise in aviation, such as persistent contrails, discussed below.

Applying Ethical Theory to Aviation

The Boeing 737 MAX

With any aircraft accident there are multiple factors that cause the crash. According to one account of the October 29, 2018, Lion Air crash, “it was caused by a combination of an improperly aligned angle of attack

(AOA) sensor, lack of pilot reporting and training as well as a breakdown in safety oversight of certification and design flaws shared between Boeing and the FAA within the aircraft's maneuvering characteristics augmentation system (MCAS)" (Bellamy 2019).

Anticipatory technology ethics could have helped forecast some of the factors in the Boeing 737 MAX accidents. Although some commentators placed blame for the Lion Air crash solely on the Boeing Company, other factors presented in the final accident report included inadequate pilot training. The need for appropriate pilot training could have been forecasted by using anticipatory technology ethics, which would have called for consideration of how the new technologies—including MCAS—in the 737 MAX would impact pilots unfamiliar with them. Had there been more emphasis on pilot training on those new technologies, the Lion Air accident might not have occurred.

Anticipatory technology ethics is also relevant to the practice of human-machine teaming, described by J-P. Clarke and Claire Tomlin (2020, p. 46). They explain that "the role of and relationship between humans and machines are optimized based on their individual and collective capabilities," adding that such teamwork "is critical to achieving safe and efficient (economic and environmental) operations."

*Anticipatory ethics
can be a helpful tool
for creating measures
to slow the spread
of disease.*

Two lessons from the Boeing 737 MAX accidents are that, to achieve this optimal level of teamwork, (1) the automated agent needs to be functioning correctly, unlike the improperly calibrated AOA sensor on the Lion Air aircraft, and (2) the human agent needs to have sufficient knowledge of how the automation operates. In the case of the Lion Air accident, one set of pilots knew how to deactivate the MCAS technology while the other crew tragically lacked the knowledge necessary to regain control of the aircraft.

Air Travel and the Spread of Disease

Another important example of how anticipatory ethics may apply to aviation concerns the role of aircraft in carrying disease. Prior to the covid-19 outbreak research had already shown that diseases spread onboard aircraft. Analysis of data related to US air travel and the incidence of influenza from 1996 to 2005 found that commercial air travel in November was a significant predictor of influenza spread (Kolmes 2019b). However, the same analysis showed that "airline restrictions would do little to slow the spread of the disease unless most air travel were to cease immediately after the beginning of the epidemic spread was detected" (Kolmes 2019b, p. 268). This finding eerily presages the covid-19 pandemic in which flight service from China was suspended too late to prevent the rapid spread of the novel coronavirus.

Given the unlikelihood of restricting air travel in a timely manner, anticipatory ethics can be a helpful tool for creating other measures. Protective measures might include preventing people with infectious diseases from boarding a commercial aircraft, increasing cabin ventilation in regions with disease outbreaks (although this would increase fuel demand), carefully disinfecting aircraft between flights, and requiring commercial aircraft to have high-efficiency particulate air (HEPA)-filtered ventilation systems (Kolmes 2019b). These suggestions were published before the covid-19 pandemic, revealing the possibility of effectively forecasting future concerns to guide decision making both at the design stage and in operations.

Persistent Contrails and the Environment

While anticipatory technology ethics can aid in decision making in the above-mentioned cases, it cannot solve all problems associated with aircraft design. One such issue concerns persistent contrails, which occur in certain conditions when aircraft are flying at altitudes of 33,000–35,000 feet and when atmospheric humidity and temperature produce ice crystal formation in the exhaust (Kolmes 2019a).

Although usually short-lived, under some atmospheric conditions contrails can spread and last for long periods, forming cirrus clouds with a heat-trapping effect. But different modeling approaches produce different estimates of the contrails' contribution to global warming (Kolmes 2019a). This example illustrates a challenge of applying consequentialist approaches such as anti-

patory technology ethics. Namely, what are the best decisions to make when the potential impact is uncertain and the results are unclear?

The example of persistent contrails highlights the need for applying other ethical theories, such as deontology. A deontologist would be concerned with the moral responsibility to address the problem by emphasizing duty rather than consequences, in considering which actions apply universally. Assuming that one of the universal moral laws would be that humans have a duty to protect the environment, then at a minimum deontology would call for seeking solutions to the problem of persistent contrails regardless of the uncertainty surrounding their level of impact on climate change.

Much research remains to be done on this topic, and the ability to determine which actions to take is problematic at best. However, persistent contrails are an important topic for anyone concerned about the impact of aircraft on the climate. In this issue Alan Epstein (2020, p. 12) states that “aviation’s most pressing challenge is climate change.” Persistent contrails contribute to climate change, so environmental ethics needs to address this matter in addition to other important topics such as alternative fuels and carbon offsets.

Concluding Remarks

Commercial aviation is a complex industry that requires strong ethical decision-making skills to maintain safety. While no one ethical theory can solve all moral

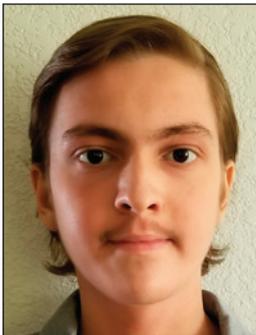
dilemmas, the application of various theories may aid in the decision-making process. The above-mentioned examples show how ethics can help in the development and use of new technologies in ways that promote both safety and the environment. The incorporation of ethical theories can point to new methods for addressing the challenges that confront the aviation industry.

References

- Bellamy W III. 2019. Lion Air 737 MAX final accident report cites AOA sensor, MCAS among multitude of contributing factors. *Avionics International*, Oct 28.
- Brey PAE. 2012. Anticipatory ethics for emerging technologies. *Nanoethics* 6:1–13.
- Clarke JPB, Tomlin CJ. 2020. Some steps toward autonomy in aeronautics. *Bridge* 50(2):43–50.
- Epstein AH. 2020. Aeropropulsion: Advances, opportunities, and challenges. *Bridge* 50(2):8–14.
- Garrick BJ, Mosleh A. 2020. Embracing the risk sciences to enhance air travel safety. *Bridge* 50(2):34–42.
- Kolmes SA. 2019a. Greenhouse gas emissions, persistent contrails, and commercial aviation. In: *Ethical Issues in Aviation*, 2nd ed, ed Hoppe EA. London: Routledge.
- Kolmes SA. 2019b. Ground-level pollution, invasive species, and emergent diseases. In: *Ethical Issues in Aviation*, 2nd ed, ed Hoppe EA. London: Routledge.
- Shilton K. 2015. “That’s not an architecture problem!”: Techniques and challenges for practicing anticipatory technology ethics. *iConference 2015 Proceedings*.

Current innovations show that emissions elimination is feasible and does not have to be prohibitively expensive.

Putting Out Fire ... with Gasoline? A Pragmatic Path toward Clean Fuels



Nick Margiewicz just completed his junior year at North Port High School in Sarasota County, Florida.

Nicholas C. Margiewicz

Renewables are in the limelight of economic models and there is much discussion about making the internal combustion engine (ICE) obsolete, perhaps with power sources such as batteries and hydrogen fuel cells. Yet ICE replacement may not be necessary.

The source of most transportation emissions is combustible fuels created from fossil fuels, which are also used in sectors such as industry and agriculture. Rather than hastily retrofitting or scrapping the millions of ICE-powered vehicles that are already on the road, as part of the climate agenda—a move that would cost trillions of dollars (Sachs 2019) and potentially cost millions of poorer people their mobility—a wise, holistic investment to mitigate the effects of climate change might be as simple and cost-effective as an increase in renewables research.

A carbon-free fuel to support engines powered by combustible sources such as gasoline, diesel, and propane without any major retrofits would ensure a fossil fuel-free economical and societal transition with as little risk as possible and could prevent further economic disarray in the transportation sector and in rural economies (O'Sullivan 2020).

Background

Over the years, technological advances and stricter, industrywide emissions standards and regulations have made internal combustion engines

more efficient and less polluting (Park 2019), as have fuel formulations. Despite this, concerns remain about their emission contributions to climate change, propelling countries to push for electric vehicle use (through incentives and rebates) in preparation for bans on these engines. Mass electrification of the transportation fleet is seen as the lowest-carbon choice. But as politicians impose increasingly stringent policies on ICE-powered vehicles, there might not be enough time for battery electric vehicle (BEV) technologies to prosper to the point of functioning as well as the former.

Meeting the needs of both personal mobility and personal/public health without having to sacrifice the internal combustion engine would yield the best of both worlds, despite sounding contradictory to many, as, realistically, people are expected to continue using vehicles, including ICE-powered ones, for both personal and commercial purposes for decades to come.

Selected Fuel Types

Fuels vary greatly in their chemical structure from gasoline to diesel to kerosene among others, but they share a common trait: they release emissions through combustion, whereas electric and fuel cell-powered vehicles release virtually none. With the transportation sector taking most of the blame for the man-made crisis of climate change, the ideal solution would be to synthesize a carbon-neutral, if not carbon-free, fuel.

Octane is a gasoline additive that allows proper engine function. A higher-octane number indicates better resistance to engine knock. Renewable and fossil fuel-based sources of octane include methyl tertiary butyl ether (MTBE), benzene, toluene, ethylbenzene, xylene (BTEX), and ethanol (Stolark 2016). In 1921 General Motors discovered that tetraethyl lead was effective in mitigating engine knock, and it eventually became the preferred octane source, with low production costs compared to benzene and ethanol-based sources, until serious health concerns led to phaseout in the early 1970s. Leaded gasoline also damaged the catalytic converters intended to reduce emissions from models between 1975 and 1996, when it was banned altogether (except for use in aircraft) (Stolark 2016).

Biofuels, including those made through “gasification” (which turns combustible waste into biofuel and a soil conditioner via filtering of flammable chemicals and oils from biomass, leaving behind highly refined carbon mixed with ash; Karikehalli 2019), and fuels blended with “drop-in” material such as ethanol are proven to

lower but not eliminate tailpipe emissions from ICE-powered vehicles (Loyola 2019). Experiments with other transportation fuels such as ammonia are also underway. But if impacts are deemed deleterious, then these specific fuels should not be commercialized as a carbon-neutral—let alone emission-free—alternative to traditional gasoline and diesel fuel.

Natural gas is not a viable solution as emissions are still released (Kusnetz 2019) and have methane as a major component (UCS 2014). Even hydrogen internal combustion engines produce emissions and are less viable than fuel cell electric vehicles (FCEVs). Hydrogen, as a primary element, has always presented difficulty with adoption for use as fuel, as incidents such as the 1937 Hindenburg crash (Lampton 2008) and hydrogen station explosions (Lambert 2019) have made the public wary. Hydrogen combusts when the volumetric ratio of hydrogen to air is as little as 4 percent. Extremely reactive, it also takes only one tenth of the amount of energy to burn similarly to gasoline, so even static electricity can trigger a violent reaction (Lampton 2008).

*Carbon-free fuel
is needed to support engines
powered by combustible
sources such as gasoline,
diesel, and propane
without any major retrofits.*

Hydrogen presents a number of other complicating factors. Although it rapidly disperses into the atmosphere in the right conditions, any resulting flames are so faint that putting one out is difficult and dangerous as one could get burned trying to locate the fire. In addition, even small amounts of air can taint the supply in an FCEV fuel tank (Lampton 2008). And hydrogen fuel cells can produce carbon monoxide and thus make the fuel poisonous like gasoline (Service 2010).

Criteria for an Ideal Fuel

The ideal fuel will serve the function of both combustible fuels used for various purposes (e.g., gasoline, diesel, kerosene, heavy fuel oil) and any alternative fuel that is

TABLE 1 Heat values of selected fuels

| Fuel | Energy density (megajoules/kg) |
|--|--------------------------------|
| Hydrogen (H ₂) | 120–142 |
| Methane (CH ₄) | 50–55 |
| Liquefied petroleum gas (LPG) | 46–51 |
| Petrol/gasoline | 44–46 |
| Natural gas | 42–47 |
| Diesel fuel | 42–46 |
| Dimethyl ether (DME) (CH ₃ OCH ₃) | 29 |
| Methanol (CH ₃ OH) | 22.7 |

Source: Adapted from World Nuclear Association (2018).

not considered carbon-neutral (e.g., natural gas/CNG). Depending on its energy density and formulation, the fuel may be more efficient, while vehicle power may decrease, remain the same, or even increase. To function most like gasoline and diesel fuel, for example, the energy density to beat is 44–46 megajoules per kilogram (MJ/kg) and 42–46 MJ/kg, respectively (table 1).

Such a fuel might allow ICE-powered vehicles to circumvent taxes and bans because emissions would be substantially, if not completely, eliminated. It would make reaching the desired 350 parts per million (ppm) CO₂ and the ambitious 1.5°C global warming threshold of the Paris Climate Agreement by 2050 more feasible, and even make it possible to achieve both goals much sooner. In the United States, this would eliminate the potential problem of Transportation and Climate Initiative states¹ losing business to nonparticipating states, while still supporting ICE-powered vehicles (Schoenberg 2019). It would also nullify artificial price hikes on these vehicles due to their emissions, making personal mobility more accessible to those of lower incomes.

A formulation that supports older cars that were designed to run on leaded gasoline and are vulnerable to even the slightest amount of ethanol in modern gasoline (including E10) is also reasonable. Lead substitutes exist as additives for these vehicles (Redex 2019), along with ethanol fuel filters (CAR Magazine 2018), ethanol-free gasoline that can be ordered online (Siegel 2018), and

¹ The Transportation and Climate Initiative is a regional collaboration of 12 Northeast and Mid-Atlantic states (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia) and the District of Columbia that seeks to improve transportation, develop the clean energy economy, and reduce carbon emissions from the transportation sector.

replacement parts to minimize effects on their engines. Without them, old leaded fuel-dependent vehicles would have gone to the scrapyard by the millions—a fate that ICE-powered vehicles may face in the near future, except the few that are donated to museums.²

Potential Fuel Alternatives

CO₂ Use

Although CO₂ is one of the main greenhouse gases contributing to climate change, as a raw material it allows fuel to be far less polluting than traditional gasoline made of petroleum from oil refineries. Emissions-to-fuel technologies are a step closer to achieving carbon-neutral fuel. Carbon Engineering, based in Squamish, British Columbia, utilizes a direct air capture system to create synthetic gas (syngas) by capturing CO₂ from the atmosphere and, with just water and hydrogen, forms a pipeline-ready gas (Conca 2019).

A similar process involves carbon mixing with H₂ generated from photoelectrolysis of water, which yields methane and water, before producing electricity through a combustion system that releases these emissions before recycling them (Hashimoto 2018). However, processes that use less, if any, water must be seriously considered so as not to burden the world's water supplies (Rosa et al. 2020).

Furthermore, MIT postdoc Sahag Voskian and chemical engineering professor T. Alan Hatton have developed a device to capture carbon at any concentration, even below the 400 ppm naturally found in the atmosphere, allowing for virtual elimination of the element in the air (Chandler 2019). It is a stack of large electrochemical plates resembling a battery that takes in CO₂ as polyanthroquinone-coated electrodes charge as the compound is attracted to them; the reverse reaction occurs once the battery is discharged. A prototypical battery, it is expected to be cost-effective over time and make it even easier to remove emissions (Chandler 2019).

Although it might be argued that it may already be “too late” to commercialize these fuels (which were all but ignored for decades), for society to continue to

² Before turning to the use of the new alternative fuels, owners of existing ICE-powered vehicles would clean out deposits accumulated in their engines. This process might involve special equipment that electrolyzes water to split H₂O molecules into oxyhydrogen to initiate a chemical reaction that strips the deposits so that they are expelled through pressure from the exhaust system.

function as normal, it really is “better late than never.” British sports car manufacturer McLaren, which plans to hybridize its lineup by the middle of the decade, has expressed interest in developing a synthetic fuel. COO Jens Ludman pointed out that the technology for developing syngas from solar energy exists and has potential to be used in ICEs with little modification (Hood 2020). He also acknowledged that some emissions would be present but would end up producing as much lifetime emissions as batteries, including those from production (Hood 2020).

According to a Bosch (2017) study, benefits from the commercialization of such fuel include not only allowing older vehicles with ICE technologies to stay on the road (coexisting with BEVs), but also reducing treatment costs, and the same applies with hybrid car ownership costs after 160,000 kilometers (99,419 miles). In addition, the existing filling station infrastructure can remain in use. Although the relatively new technology will be expensive at first, Bosch predicts that average costs will eventually plummet to between €1.00/liter (\$1.08/gallon) and €1.40 (\$1.52)—cheaper than gasoline (Bosch 2017).

“Power-to-X” technologies could see other forms of energy, including electricity, helping to advance progress toward “green gasoline” that can take the form of other fuels such as diesel and kerosene. Also using CO₂ as a base, Chemieanlagenbau Chemnitz (2019) and Mitsubishi Hitachi Power Systems GmbH constructed a complete process chain using hydroelectric power generation.

Photosynthesis, Catalysis

Another benchmark is an “artificial leaf” created by the University of Cambridge (2019). Inspired by the natural process of photosynthesis, a device consisting of two light absorbers and a cobalt catalyst is submerged underwater, where one absorber (BiVO₄) produces oxygen with a reaction from the catalyst via exposure to a blue light while the other (perovskite, CaTiO₃) uses another chemical reaction to dilute CO₂ to produce carbon monoxide and hydrogen (Jasi 2019). Even though this promises a sustainable liquid fuel alternative produced with a much cleaner process, environmental concerns are sparked by the use of carbon monoxide. Also, while it can still be used on rainy and/or cloudy days (University of Cambridge 2019) it does not match the energy density of natural gas, but there is room for improvement (Satherley 2019).

Low-cost molybdenum nanoparticle catalysts have been developed by chemists at the University of Southern California for Carbon Recycling International’s George Olah Plant in Iceland, which captures emissions from the nearby Svartsengi Power Station. The catalysts mix with the emissions to perform chemical reactions similar to those in combustion, such as splitting carbon-oxygen bonds to form a “carbon-neutral” hydrocarbon fuel (Oberhaus 2020).

Photosynthesis may yield a sustainable liquid fuel alternative produced with a much cleaner process.

Synthetic fuels that are part of the oxymethylene ethers group are being assessed on a single-cylinder testbed in trials done by the Technical University of Munich, funded by the German Federal Ministry of Economics, under the XME Diesel project (Wilkes 2020). Results showed that because the fuel has a lower calorific value than traditional diesel, more must be put into the engine to achieve the same performance, and so the injectors had to be modified. Pollutants are nevertheless cut to the point of meeting current Euro 6 standards, giving cars retired from European roads because of increasing taxes and failed emissions tests a second life back on the roads (Meinecke 2018).

Hydrogen

While hydrogen alone is unsuitable for traditional internal combustion engines without modifications (as discussed above), it can be used as a base in synthetic fuel, and demand is expected to skyrocket thanks to Canada-based Proton Technologies’ Hygienic Earth Energy concept (Collins 2020).

At existing oil fields (operational, abandoned, or defunct), air and/or oxygen is channeled into the reservoir or coal bed where hydrocarbons are ignited, and when the fire’s temperature exceeds 500°C (932°F), injected steam and/or water vapor reacts with the hydrocarbons, creating the syngas. Additional water would spark yet another reaction that releases even more CO₂ and hydrogen—without impurities (includ-

ing CO₂), as patented palladium-alloy membranes allow only the hydrogen through a metal lattice.

Hydrogen could be produced for as little as 10¢–50¢ per kilogram. Even green hydrogen—which is split from water molecules and also consists of oxygen with renewable energy, costing \$2.50–\$6.80 right now—would cost \$1.40/kg and 80¢/kg by 2030 and 2050, respectively (Collins 2020).

Research

All these methods can close the global carbon cycle, with carbon capture/emissions reduction as the first line of defense. However, prevention of both environmental problems and a backlash requires further progress, research, and innovation for a truly “carbon-neutral” fuel, so these solutions, which all use CO₂ as a base, are not yet viable in the long run.

*A fuel made
of metal powders
(e.g., aluminum, lithium,
magnesium, zinc) has a
much higher energy density
than hydrogen and batteries.*

Researchers at McGill University and the European Space Agency have developed a fuel designed for external combustion engines that is made of various metal powders such as aluminum, lithium, magnesium, silicon, and zinc (similar materials are already used for rocket fuel) (Hellemans 2015). Although metals have the advantages of easily recyclable outputs (iron oxide) and a much higher energy density than hydrogen and batteries, they should not be entirely relied on to cancel out emissions because of concerns about heavy metal poisoning and toxicity for wildlife, soil, and water (symptoms vary by type of metal; Tchounwou et al. 2012).

Beyond the Automobile

The scope of proposed alternative fuels should not be limited to automobiles. The aviation industry has its own complicated emissions elimination problem. JetBlue’s plan to become carbon-neutral by June 2020,

aside from through carbon-offsetting projects, is to use a sustainable aviation fuel for flights departing from San Francisco International Airport (Stevens 2020). Widespread implementation of such fuel would mean a much cleaner and safer tourism industry.

An example of a sustainable aviation fuel option is a synthetic fuel pioneered by Dutch company Urban Crossovers, with CO₂ sourced by Swiss environmental company Climeworks (which can also sequester the compound underground) (Beard 2019). Another is fuel that uses power-to-X technologies to create a water-based kerosene also using carbon capture for formulation. The latter was pioneered in Germany in 1925 and was intended to be used by Hitler’s Luftwaffe (Stevens 2020), in response to an oil embargo during the Great Depression.

The agricultural and industrial sectors can also benefit from these proposed fuels. Current postharvest processing and marketing made possible from efficient mechanization cannot be considered environmentally friendly if ICE-powered machinery is used.

Conclusion

Once new alternative fuels are produced and commercialized to the point of being affordable, they can easily be applied to all types of ICE-powered transport (Sachs 2019), allowing for more resilient energy supplies (Prentiss 2019) and clean economic growth. Such innovation is proof that emissions elimination does not need to be prohibitively expensive in the long run, and that it will not be necessary to scrap millions of ICE-powered vehicles, whether they run perfectly or not.

In the near future, greenhouse emissions will no longer be treated as the root of all evil, but as a valuable economic commodity when captured and/or filtered quickly enough, kickstarting the next gold rush out of thin air.

References

- Beard S. 2019. A new jet fuel offers the prospect of no-carbon, “guilt-free” flying. Marketplace, Oct 10.
- Bosch. 2017. Carbon-neutral cars: Synthetic fuels turn CO into a raw material. Press release, Aug 22.
- CAR Magazine. 2018. How to protect your classic car from fuel ethanol products. Dec 15.
- Chandler D. 2019. MIT engineers develop a new way to remove carbon dioxide from air. MIT News, Oct 24.
- Chemieanlagenbau Chemnitz GmbH (CAC). 2019. Green fuel is already market-ready. OpenPR, Dec 20.

- Collins L. 2020. Low-cost, clean hydrogen from underground oil fires could kill off green H2 sector. Recharge, Feb 7.
- Conca J. 2019. Carbon Engineering: Taking CO2 right out of the air to make gasoline. Forbes, Oct 8.
- Hashimoto K. 2018. For sustainable development of the whole world by renewable energy. *Journal of Fundamentals of Renewable Energy and Applications* 8.
- Hellemans A. 2015. Metal powder: The new zero-carbon fuel? *IEEE Spectrum*, Dec 16.
- Hood B. 2020. McLaren will explore synthetic fuels as an alternative to electric cars. Robb Report, Apr 10.
- Jasi A. 2019. "Artificial leaf" for carbon neutral syngas production. *Chemical Engineer*, Dec 23.
- Karrikehalli S. 2019. Professor's waste-to-energy invention to be commercialized. *Daily Star*, Dec 22.
- Kusnetz N. 2019. Natural gas rush drives a global rise in fossil fuel emissions. *Inside Climate News*, Dec 3.
- Lambert F. 2019. Hydrogen station explodes, Toyota halts sales of fuel cell cars, is this the end? *Electrek*, Jun 11.
- Lampton C. 2008. What are the dangers of hydrogen-powered vehicles? *HowStuffWorks.com*, Sep 4.
- Loyola M. 2019. Ethanol has forsaken us. *The Atlantic*, Nov 23.
- Meinecke V. 2018. On the road to a clean combustion engine. *Technical University of Munich*, Sep 5.
- O'Sullivan K. 2020. Electric cars will be more economical than petrol, diesel within four years – Bruton. *Irish Times*, Jan 6.
- Oberhaus D. 2020. Cheap nanoparticles pave the way for carbon-neutral fuel. *Wired*, Feb 19.
- Park J. 2019. Eaton looks to advanced engine technology to combat emissions. *Heavy Duty Trucking – Truckinginfo*, Apr 8.
- Prentiss M. 2019. The technical path to zero carbon. *American Prospect*, Dec 5.
- Redex. 2019. What fuel should you use in your classic car? Oct 30.
- Rosa L, Reimer JA, Went MS, D'Orico P. 2020. Hydrological limits to carbon capture and storage. *Nature*, May 4.
- Sachs J. 2019. Getting to a carbon-free economy. *American Prospect*, Dec 5.
- Satherley D. 2019. New artificial leaf could one day make carbon-neutral jet fuel. *Newshub*, Oct 25.
- Schoenberg S. 2019. Higher prices for cleaner air? What is the Transportation and Climate Initiative? *MassLive*, Dec 16.
- Service RM. 2010. The case of the poisoned fuel cell. *Science*, Jul 16.
- Siegel R. 2018. Choosing the right fuel will protect your classic. *Hagerty*, Aug 13.
- Stevens P. 2020. JetBlue announces plans to become carbon neutral on domestic flights in a first for the US airline industry. *CNBC*, Jan 6.
- Stolark J. 2016. A brief history of octane in gasoline: From lead to ethanol. Fact sheet, Mar 30. Washington: Environmental and Energy Study Institute.
- Tchounwou PB, Yedjou CG, Patlolla AK, Sutton DJ. 2012. Heavy metal toxicity and the environment. *Experientia Supplementum* 101:133–64.
- UCS [Union of Concerned Scientists]. 2014. Environmental impacts of natural gas. Jun 19.
- University of Cambridge. 2019. "Artificial leaf" successfully produces clean gas. *ScienceDaily*, Oct 21.
- Wilkes W. 2020. Germany looks for flight shame cure in jet fuel made from water. *Bloomberg Green*, Jan 30.
- World Nuclear Association. 2018. Facts and figures: Heat values of various fuels. London.

An Interview with . . .

Lisa Eastep, Metallurgist and Roller Derby Competitor



Lisa Eastep

RON LATANISION (RML): Lisa, it's good to talk with you, what with the disruptions of the coronavirus pandemic. How are things in Rhode Island?

LISA EASTEP: The state started opening this week.

RML: What does that look like?

DR. EASTEP: Restaurants are open for outdoor service. Retail stores are open but they're limiting how many people go in. Still no personal services, like haircuts. No concerts or sporting events. Movie theaters are still closed. But the one drive-in in the state will open this weekend. So the opening is limited. There are more people out and about than there were, but I don't think we ever shut down to the same extent you did in Massachusetts.

RML: Yes. We're on a downward trend in terms of hospitalizations and deaths, but it's still a challenge.

This conversation took place May 12, 2020. It has been edited for length and clarity.

Lisa, you and I have known each other quite a while—we joined Exponent within a year of each other. When did you join Exponent?

DR. EASTEP: It was right after my son was born, so it was 2003.

RML: And I joined Exponent in 2002. Then you went to work at Failure Analysis and Prevention in North Kingstown, Rhode Island, several years later. When was that?

DR. EASTEP: 2009. I spent about 6 years at Exponent.

RML: So I've known you as a metallurgist for quite a while. You're a physical metallurgist, is that right?

DR. EASTEP: Yes.

RML: And you've been practicing for quite a few years, so you have a lot of experience as a metallurgist. Let's start by hearing a little about your metallurgical history.

DR. EASTEP: I got my undergraduate degree in physical metallurgy in 1993, from Cal Poly in San Luis Obispo. Then I got my first consulting gig that summer—I helped a professor, who was consulting. I was sort of the grunt, I did some lab work. The next year I started on my master's degree at Cal Poly. I got my PhD in process metallurgy from Carnegie Mellon in 2000, and then spent 3 years in a steel mill because I needed to get real-world experience before jumping into consulting full-time.

RML: What steel company?

DR. EASTEP: It's sort of a unicorn in the steel industry, a small, privately held, family-run business called Ellwood Quality Steels. We made carbon and alloy steel for the forging industry—we'd produce the ingots that Scot Forge, Patriot Forge, Wyman Gordon, and others would turn into the final product.

RML: Where is it located?

DR. EASTEP: Sixty miles north of Pittsburgh in New Castle, Pennsylvania.

RML: I know that area. And who was your advisor at Carnegie Mellon?

DR. EASTEP: Dick Fruehan, and the research group was called the Center for Iron and Steelmaking Research. It was a private company–education partnership where steelmaking-related companies would pay an annual fee and guide the research based on challenges in the industry.

RML: What was your thesis topic?

DR. EASTEP: Postcombustion in an electric arc furnace. In the steelmaking industry, they're always looking for ways to increase energy efficiency. One way is to use an electric arc furnace, with large graphite electrodes to create small lightning bolts in order to melt large quantities of scrap. This method produces a lot of carbon monoxide because there's a lot of carbon involved.

There was a big push in the industry to use every bit of electric energy that you could to reduce the amount of electricity required. By burning carbon monoxide to carbon dioxide, you could get a lot of energy. Now, as you know, Ron, carbon dioxide and high temperatures in metal are not always the best combination.

We were looking at how much energy we might get by burning carbon monoxide to carbon dioxide, and what the ramifications might be when the carbon dioxide comes in contact with the metal. I did some computational fluid dynamics modeling of the electric arc furnace and simultaneously did kinetic experiments of iron in a carbon dioxide-rich environment at elevated temperatures, around 1477K and up to 1600K. That was my research. I tried to marry the modeling and the lab work and the conclusion of my research was don't do it.

RML: As I listen to you describe your thesis, you sound like a chemical metallurgist.

DR. EASTEP: Actually, I'm both, but where I've chosen to take my career is almost 100 percent physical metallurgy. I learned working at the mill that I like physical metallurgy so much better. I like to be able to touch the metals I'm working with; with chemical metallurgy, it's a little too hot—you can observe, but there's not a lot of touching.

My undergraduate work was in physical metallurgy and I got really curious about how to get steel to be steel. Then I did my PhD work in chemical metallurgy. I

like to look at everything—from when it's in the ground until you melt it—but ultimately I directed my career to physical metallurgy.

RML: The steel industry certainly has changed a lot since you were at Ellwood Quality Steels.

DR. EASTEP: Yes, it has.

RML: My wife Carolyn grew up in Bethlehem, Pennsylvania, and she's a painter. A few years ago, when she learned that Bethlehem Steel was going out of business, she became very nostalgic. She had lived within blocks of the blast furnaces, with the noise and odors and everything. And everybody in her family worked in the steel mills in one place or another. She arranged to do some paintings at Bethlehem Steel and got an escorted tour of the steel mill before they started dismantling it. Her paintings show how the industry has changed. One of my favorites is of a blast furnace with weeds growing around it and no smoke belching from the stacks. It's a testimonial to the silence of that part of the industry. You've seen both ends of that spectrum.

*I like physical metallurgy
better than chemical
metallurgy because
I like to be able to touch
the metals I'm working with.*

DR. EASTEP: Yes. When I was still living in Pittsburgh, US Steel at their Monroeville facility, which is the second oldest integrated steel mill in the country (the oldest being at Edgar Thomson Steel Works in Braddock, PA), actually had a blast furnace from the late 1800s that was still in use.

RML: And the Bethlehem Steel plant was over 100 years old when they decided to go out of business and retire everything.

CAMERON FLETCHER (CHF): Lisa, I gather you now live in Rhode Island. How do you like it?

DR. EASTEP: I love Rhode Island. It's a supersmall state and we live in a supersmall town on an island in Narragansett Bay. It's the complete opposite of when I was living in the Bay Area in California.

CHF: Yes indeed. And I understand that's where you got started in roller derby.

RML: You must be athletic by nature?

DR. EASTEP: Yes, I've always been very active. "Athletic" sounds like I have actual talent; let's just say I'm very active. I don't know that I was ever at the top of any skill level. I like hiking, and when I was in grad school, I used to run. I've always been extremely active.

CHF: How did you get into roller derby?

DR. EASTEP: We moved to Rhode Island and, as any good New Englander, we decided to get my son into ice skating because that's what you do in New England: you learn how to ice skate. He really seemed to enjoy it. And then one day he decided he didn't want to do it anymore. My husband and I thought, 'Maybe there's something about the ice he doesn't like. Let's see if he would like roller skating.' We took him to the local roller rink and he seemed to enjoy himself. That rink was also where the Providence Roller Derby used to practice.

*A lot of engineering
goes into the skate
for it to be able to withstand
stresses in loading and
still be lightweight.*

We would go to the roller rink every weekend and there was one corner where the roller derby players hung out. My son was fascinated with them. I would watch them and I'd be a conceited, arrogant individual thinking 'I can do that.' After a couple of years of telling myself that, I decided, 'All right, let's see if I can do that,' so I joined up.

I'd been roller skating my whole life, but not in a way that I hit people, which is a whole different new skill set. That's how I got involved. It took me about 10 minutes to fall in love with the sport.

CHF: What made you tell yourself 'I can do that'? You said you'd been roller skating your whole life, which is in itself a little unusual, but there was apparently something about the physical—I'll call it "engagement" of the sport that appealed to you.

DR. EASTEP: I grew up in Southern California in the late '70s, early '80s, so roller skating was a rite of passage. Everybody did it. I think another aspect of this was a midlife crisis. It was my 40th birthday when my husband got me a pair of derby skates.

I grew up watching roller derby on TV. There was a *Charlie's Angels* episode, and I remember watching a Raquel Welch movie, *Kansas City Bomber*. So I had these Hollywood visions of it, and a whole lot of midlife crisis thrown in, that made me decide that I could do this.

The other aspect is that I was looking for opportunities to meet people. I work for a small company in a male-dominated field, so there's not a lot of opportunities to engage and get to know other women. My husband is a stay-at-home parent, so he handles PTA meetings and stuff like that. So this was a way for me to meet new people.

CHF: That makes sense. You mentioned derby skates. What's different about those?

DR. EASTEP: If you watch figure skating, you'll see that there's about a 1-inch heel at the back and skaters spend a lot of time up on the balls of their feet. Derby skates don't have that heel and you spend a lot more time in roller derby on your heels because that's usually where you get a lot of your power and stopping capability. And the boots don't come up your ankle so they don't impair your movement. We call them low-ride boots, with no heel. That's what's considered a roller derby skate. And of course there are four wheels on it, it's called quad wheel. The boot sits on a plate and the wheels screw into the plate. There's a lot of engineering that goes into the plate for it to be able to withstand the type of stresses in loading and still be lightweight.

RML: I was going to ask whether your experience as a metallurgist entered at all into your venture as a roller derby skater. Sounds like it has because the materials and construction are part of the equation.

DR. EASTEP: Absolutely. Not so much the metallurgy, but the materials science. The way the materials of the wheel interface with the surface you're skating on affects your stability and your ability to stop, for example.

We (Providence Roller Derby) don't have a "home" so we don't have a specific facility where we practice or compete. We compete on a bunch of different surfaces.

When I first joined the league, one of the places where we were skating is a high school gymnasium,

which has a basketball floor with polyurethane coating that's designed for feet to not skid—which is really good for basketball and volleyball and really bad for your elbow pads and knee pads: When you fall, your elbow pads and knee pads stick to the floor and instead of sliding, which helps dissipate the movement, you end up going heels over head.

When I first started doing this, I thought, 'there has to be some type of coating or material that we could use.' I did experiments with a bunch of different spray-on coatings and finally figured out that Teflon tape—the kind of tape that you would use on the interior of air ducts—allows really good sliding. When you put Teflon tape over the surfaces of your knee pads and elbow pads, it helps a tremendous amount. It's not perfect, but it helps.

CHF: I bet your teammates appreciated that.

DR. EASTEP: They did actually. They didn't believe me at first. 'What is this rookie trying to tell us about how to do what we're supposed to do?' They found out that some of the other leagues around the world were doing something quite similar. So it wasn't like it was my unique idea, but it validated my experiments. My teammates bought into my results a lot faster when they found out some of the other leagues were doing the exact same thing.

RML: It sounds like you also earned your derby name, Dr. Steelgood. How did your name come about?

DR. EASTEP: Everybody has a cool name. I have a PhD in steel making, and I like the Mötley Crüe song "Dr. Feelgood" (as long as you don't listen to the lyrics too closely because it's about a drug dealer; I went back and listened to the lyrics after I chose my name and cringed). And then my roller derby number is the atomic mass of iron—it's 55.85.

CHF: That is so fabulously nerdy. You are really making the most of it. Well done.

DR. EASTEP: Thank you very much.

RML: How do you balance your workload and your skating? How much time practicing and competing is typical?

DR. EASTEP: A lot. There are two aspects to the league. I liken it to Little League baseball. We have what we call a home season or home teams, which is the equivalent of recreational, and we have travel teams,



Dr. Steelgood.

like the Little League all-star teams that travel. The travel team is the competitive team, traveling around the country and up to Canada sometimes. I'm on both teams, travel and home.

The travel team is very, very competitive. We all belong to the Women's Flat Track Derby Association (WFTDA), which has about 400 leagues worldwide. Providence Roller Derby was the first league to form in New England; we just celebrated our 15th anniversary. We're currently ranked about 80 out of 400—not the top, but very decently placed.

Practice schedule for the travel team is 6 hours a week. I have two 2-hour practices and a 2-hour scrimmage every week for the travel team plus another 2-hour practice with the rest of the league. We usually play in two or three tournaments a year and then some individual games. A tournament is usually a 2- to 3-day event. Depending on how it's set up, we can play between two



The physical nature of roller derby.

and maybe five bouts over a weekend. A lot of these tournaments are set up similarly to the NCAA basketball tournaments. You go in and as you keep winning, you play more. Last summer we were up in Canada and I think we played five games over 2 days.

RML: A game is two 30-minute periods, is that right?

DR. EASTEP: Correct. Two 30-minute periods and then a 15-minute half-time usually.

RML: I'm looking at a list of the Providence Roller Derby team names. Which team are you on?

DR. EASTEP: I'm on the Killah Bees and the Sakonnet River Roller Rats.

RML: I notice that you've been an all-star at least twice, maybe more, and on the traveling team. You have to be a pretty competitive skater.

DR. EASTEP: I'm an incredibly competitive person. But I would say that among the competitive skaters in the league, I'm at the lower end of average. It takes me a little longer than some of the young whippersnappers to pick up some of the skills. I'm in my fourth season on the travel team right now, and I'm in the middle as far as skill level is concerned.

CHF: You mentioned "young whippersnappers." What's the age range of derby skaters? It sounds pretty taxing

physically. What are the ages of the oldest competitors?

DR. EASTEP: In our league, ages range from 18 to mid-50s; the median age is probably early 30s. I'll be 49 in November and I'm one of the oldest skaters. There are two skaters who are older than I am; one of them, who just retired after I think 10 years, is in her mid-50s. A skater I know in Connecticut is 62 and she's still going. There's also a junior roller derby league for ages 8 to 17.

RML: I'm looking at some of the other team names. The Rhode Island Riveters, the Mob Squad, the Old Money Honeys. There seems to be a lot of spirit in the choice of names for both the players and the teams. Is that part of the sport and its history?

DR. EASTEP: It's the culture and history. There are a couple different aspects. There's the pun involved and there's also sort of a 1950s pinup girl vibe. You also want to encompass the flavor, if you will, of your region. That's why we're the Rhode Island Riveters, acknowledging Rhode Island and its military history. The Killah Bees is based on the Navy Seabees; our logo is the same as the Construction Battalion. The Old Money Honeys are based in Newport. The Federal Hill Mob Squad plays to the fact that Providence is associated with organized crime and has a huge Italian community. Organized crime was active in Providence through the '80s and '90s.

In New York City, Gotham City is the name of their roller derby league. And there are the Brooklyn Bombshells and Wall Street Traitors. So the different locations try to express a flavor of their region.

CHF: People are clearly clever about this. I'm guessing that that indicates a general sense of humor, which would also lend itself to some great camaraderie with your teammates.

DR. EASTEP: Absolutely. It's amazing. It's one of the things I really love about this sport. We're all unbelievably competitive individuals—you don't do this unless you have that really competitive streak. But it's not unheard of to be at a tournament and the word to go out among all the teams that "someone broke the plate on their skate, does anybody have a plate we can use?" People share resources, supplies, whatever they can with teams that they're going to compete against in a few minutes. You can see it from the most competitive games down to the most recreational fun games where, between jams, there's usually music playing and you'll

see different teams dancing with each other.

The coolest part is that, in every bout that we play, tournament or otherwise, each team selects a valuable player from the team they just played. Usually it's most valuable blocker and most valuable jammer—basically offense and defense. So if our team played your team we would select who we thought was the best blocker and the best jammer on your team and you would select the best blocker and jammer on our team and then we would award each other something. So it's always about a certain amount of camaraderie even though we're going to beat the crud out of each other.

CHF: That's a really nice tradition. I want to ask, what are the rollers made of? I'm supposing they're a heavy-duty plastic type of material.

DR. EASTEP: You're right. It's polyurethane. The wheels are specially designed to have certain hardnesses. Remember I mentioned that we skate on different surfaces; the hardness of your wheels is going to dictate how you interface or work with the surface you're skating on.

A lot of places where we skate are decommissioned hockey rinks, so we skate on concrete a lot. As I mentioned, we also skate in gymnasiums, which have a polyurethane-coated floor. There's sometimes a sports court floor, more like a plastic tiling. Sometimes we skate outdoors on asphalt; not a favorite of mine, but that's what you do. And a roller rink has a wooden floor with some type of a wax or polyurethane coating on it. So we skate on lots of different surfaces.

CHF: And you have different skates for different surfaces?

DR. EASTEP: Different wheels if you can afford it—wheels can run about \$100 to \$200 for a set. I have a couple of teammates who can only afford one set; you make do with what you can. I have three different sets of wheels that I change out on my skates depending on where I'm skating.

CHF: You screw them on to the skate boots?

DR. EASTEP: Yes. Your skate boot, which is almost always leather (or vegan leather if you're a vegan), is bolted or screwed onto a metal or carbon fiber plate, which has axles attached to it, and the wheels are bolted to the axle.

RML: All of the skating surfaces are flat, is that correct?



Skatewheels are made of different materials for different surfaces.

DR. EASTEP: Yes. Well, generally flat, because sometimes we skate in parking lots, where flat can take on a whole new meaning. It might be a little wavy. But generally it doesn't have any kind of grade.

RML: I asked because I remember seeing some discussion about Olympic roller sports. I often saw banked tracks. For roller derby what's the significance of the transition from banked tracks to flat tracks?

DR. EASTEP: The big significance is cost. Roller derby originated in the 1930s during the Depression era when people were looking for things to do outside. Originally, it was about who could skate the longest, going around and around in circles. Then it evolved to include preventing other people from skating faster than you. That's when all the contact got involved.

It was originally designed on banked tracks because they're good for high speeds. Banked tracks became less popular during the resurgence in the early 2000s because they take a capital investment and it was sort of an underground garage type of sport. For banked tracks you have to have the space, you have to build the track, you have to maintain it. At the same time roller rinks were starting to go out of business. What spaces were easily available? Parking lots, decommissioned ice skating rinks, gymnasiums,....

CHF: Are there different team positions?

DR. EASTEP: There are three general positions on a team. On the track at any one time there are five players for each team competing against each other in what's called a jam. I use football as an analogy because I really



Blocking is an all-important aspect of the sport.

like football and I know it well. You have five people from each team on the track at any time for a jam that can last up to 2 minutes. In football you have an offensive and a defensive line for different downs. The five players include four people called blockers and one person called a jammer. The jammer's job is to skate past people and the blockers' job, obviously, is to prevent the jammer from the opposing team from skating past.

One of your blockers has a position called a pivot: if the jammer gets really tired or gets into some trouble, they can do what we call "pass the hat" or "pass the star," which is to remove a hat on top of her helmet and hand it off to the person (the pivot). Then the pivot is the jammer. Those are the three "positions" on a roller derby track.

CHF: What's the goal of each jam?

DR. EASTEP: It is quite literally to pass people. The jammer scores one point for every player they pass on the opposite team. There are four blockers on at any one time.

RML: Your blockers would help to open the path for you to do that. That's the strategy.

DR. EASTEP: Correct. The blocker is both offense and defense simultaneously, which can get a little insane.

We're there to keep the opponent's jammer from getting through—basically, again using football as an analogy, acting as the defensive lineman. And we're trying to open holes in the other team's line so that my jammer can get through, acting as an offensive lineman.

RML: Are you a jammer, a blocker, or a pivot or all three at different times?

DR. EASTEP: In practice, I'm all three. On the track, I'm primarily a blocker—I just don't have the explosive speed for jammers. But in practice I'll jam like crazy.

It's like running backs. There are two types of running backs. You have the juking kind, like Barry Sanders, who can spin and move really fast from side to side, and then you have the Jerome Bettis kind who just go and keep going and they're going to hit you and it's going to hurt. I'm more the Jerome Bettis type of jammer, which is exhausting. I don't have a lot of juking ability, I can't easily shift directions. I basically just skate really fast. If I'm skating fast enough, I will break through your walls. If I'm not, I'm going to be pushing up against your wall for a really long time. I'm primarily a blocker.

RML: I had a very good friend who sailed dragons, which are not Olympic boats, but he was very close to getting on an Olympic team at one point. Have you heard any discussion about roller derby being an Olympic-caliber sport?

DR. EASTEP: Yes. There is a push for a category with multiple roller sports. In the roller derby community, we obviously would love for it to become an Olympic sport—if we survive the covid outbreak. All our leagues are taking massive financial hits right now and I suspect that a lot of leagues will fold because they're not financially sustainable. Still, there's talk about it. We do have a World Cup every 4 years, and our own championships like other professional leagues. It's perfect for an Olympic sport.

I suspect a big challenge is that it's the only women-centric contact sport. What I mean is when you think of other sports, there's basketball and women's basketball, soccer and women's soccer. It's the reverse with roller derby: you have roller derby and men's roller derby. I think there's still a lot of difficulty from the mainstream perspective in accepting a female-centric contact sport, although I think that's changing.

RML: It just seems to bring so much camaraderie and skill, and there's a certain joy. I watched a couple of videos and it looks like a natural for an Olympic sport.

DR. EASTEP: I agree completely. But it's not well enough known. We don't have grassroots support pushing for it. Also, if you think about it, in a business like everything else, networks want something that people are interested in and want to watch. We're still pretty small from that perspective.

And yet junior roller derby is taking off now because of the camaraderie and the body-positive influences. There is no ideal body type for this sport. None. I skate against people who are 5 feet tall, weigh 100 pounds, and are very good; they're jammers and can squeeze through. And I have teammates who are 6 feet tall and weigh 250 to 300 pounds, and there's a benefit to that. There are advantages to all body types. It's great.

Starting with the junior leagues, there's the body-positive aspect to it, encouraging kids to be active and learn how to be healthy. You're basically growing both a new crop of skaters and a new audience. So with junior roller derby we're trying to spread the word to get more people interested so that we can get more visibility, which is one of the ways you make your way up to the Olympics.

CHF: That all sounds very encouraging. Thinking about the Olympics, how popular is roller derby in other parts of the world. You mentioned Canada. What other countries?

DR. EASTEP: We're in countries all around the world. If I'm remembering my statistics correctly, either New Zealand or Australia has the highest number of leagues per capita. But it's really popular everywhere—Africa, Central America, Argentina and Brazil, Britain, Europe has quite a few, I think there are even leagues in the Middle East. There's also a Team Indigenous in the United States, with Polynesians and Native Americans. So we're everywhere and we're growing. There are more than 400 leagues worldwide.

CHF: Lisa, you mentioned earlier that you used your engineering background a little in the application of the tape to prevent skidding. How else does your engineering background inform your approach to roller derby?

DR. EASTEP: That's a great question. We're trying to make our bodies do some unique and probably not very good things, and I use my engineering to figure out how to do what I want to do. For example, if I want to skate really fast around a corner that I might skid on, I

think about not wanting to go over the static friction coefficient to the floor. I don't want to go into dynamic friction, I want to stay in static friction. So what can I do? Or if I want to be able to stop my body with my feet in certain positions, where do I need to put the pressure—on the inside edges of my skates, the ball of my foot, the heel?

Basically, I do a lot of statics and dynamics even though I'm a metallurgist and my mechanical engineering friends would laugh at how basic my approach is in looking at these things. But I do try to look down and think, from a mechanical standpoint, where is the high stress point? How do I build a structure with my body that's going to be structurally sound so that when somebody flies at my back at a high rate of energy, I can dissipate their momentum? I do think that way when I'm trying to learn new skills. I break everything down from an engineering and energy and momentum perspective and then try to figure out how to make my body work.

CHF: That's terrific. Thanks for explaining that.

DR. EASTEP: And because I'm a recruitment coach, I train the new recruits. I'll say something like, "Try this with your body" and they look at me and I say "Trust me. Do you want me to draw you a free body diagram?"

One other thing I'll share about my engineering perspective. As you can imagine there are a lot of injuries in this sport. I know several people who have had broken bones, and sometimes there's hardware—stabilizers and screws. I ask people if I can have their hardware screws, especially if it's cracked or broken, I want to look at it. With one of my friends, a titanium screw broke, and I have it in the lab.

[Laughter]

CHF: That's an unusual engineer's approach to the sport.

RML: You're really earning your doctoral title every day.

CHF: Lisa, we've come to the end of our hour. Thank you so much.

RML: This has been a lot of fun. I appreciate you talking with us today.

DR. EASTEP: It was. Thank you so much for asking.

NAE News and Notes

NAE Newsmakers

Dereje Agonafer, Presidential Distinguished Professor, University of Texas at Arlington, is the recipient of Howard University's **Alumni Award for Distinguished Postgraduate Achievement**, honoring alumni who have made valuable contributions in their field.

Kristi S. Anseth, Tisone Professor and distinguished professor, Department of Chemical and Biological Engineering, University of Colorado Boulder, has received one of the most prestigious recognitions in the life sciences: the **L'Oréal-UNESCO for Women in Science Award**, which seeks to increase the representation and awareness of women in science and their achievements to inspire more women to consider careers in the sciences. Dr. Anseth received the award for her "outstanding contribution in converging engineering and biology to develop innovative biomaterials that help tissue regeneration and drug delivery."

George H. Born, professor of aerospace engineering sciences and director emeritus, Colorado Center for Astrodynamics Research, University of Colorado Boulder, was elected posthumously to the **Colorado Space Heroes Hall of Fame** on February 26. The award is presented every two years to Colorado residents who have made contributions in the space arena that span a decade or more. Dr. Born was recognized for seminal work in the fields of astrodynamics and remote sensing that has profoundly impacted our ability to observe and understand our changing Earth.

Anjan Bose, Regents Professor, School of EECS, Washington State University, was elected a **foreign member of the Chinese Academy of Engineering** in November 2019, recognized for his "distinguished contributions to electric power engineering and to the promotion of China-America exchanges and cooperation in this field." His induction will be held in early June during the 2020 CAE annual meeting in Beijing.

John A. Cherry, distinguished professor emeritus, University of Waterloo, and adjunct professor, University of Guelph, has received the **Stockholm Water Prize 2020** for discoveries that have revolutionized understanding of groundwater vulnerability. His research has raised awareness of how groundwater contamination is growing across the world and has led to new, more efficient methods to tackle the problem. The prize, awarded by the Stockholm International Water Institute (SIWI) in cooperation with the Royal Swedish Academy of Sciences, will be presented to Dr. Cherry by Swedish King Carl XVI Gustaf, official patron of the prize. The ceremony and a royal banquet will be held at the Stockholm City Hall as part of World Water Week in August.

Charles Elachi, professor emeritus, electrical engineering and planetary science, California Institute of Technology, has been awarded the **2020 Michael Collins Trophy for Lifetime Achievement**. The Smithsonian's National Air and

Space Museum presents the trophy for "outstanding achievements in the fields of aerospace science and technology and their history." The trophy, renamed this year in honor of Michael Collins, pilot of the Apollo 11 command module, was scheduled to be presented to Dr. Elachi March 26 at the museum.

Eric R. Fossum, John H. Krehbiel Sr. Professor for Emerging Technologies and associate provost, Thayer School of Engineering, Dartmouth College, was chosen by the Optical Society (OSA) and the Society for Imaging Science and Technology (IS&T) to receive the **2020 Edwin H. Land Medal**. Professor Fossum is recognized for the invention and commercialization of advanced CMOS optical sensor imaging technology and the quanta image sensor, and for university entrepreneurial and national young inventor training activities. Established in 1992, the Edwin H. Land Medal recognizes pioneering work empowered by scientific research to create inventions, technologies, and products.

Andrea Goldsmith, Stephen Harris Professor of Engineering, Stanford University, has received the highest honor in telecommunications research—the **Marconi Prize**. She is the first woman in the award's 45-year history to win the prize, which is awarded annually to innovators who have made a significant contribution to increasing digital inclusivity through the advancement of information and communications technology. Dr. Goldsmith received the honor for

her pioneering contributions to the theory and practice of adaptive wireless communications.

Yonggang Huang, Walter P. Murphy Professor of Engineering, Northwestern University, and **Gary S. May**, chancellor, University of California, Davis, have been elected **members of the American Academy of Arts and Sciences**.

West Virginia State University has established the **Dr. George E. Keller II Memorial Scholarship** in honor of **George E. Keller II**, chief engineer, Mid-Atlantic Technology, Research, and Innovation Center. The endowed scholarship will go to full-time students seeking a degree in chemistry or chemical engineering and pursuing an internship in the chemical industry.

The **American Concrete Institute** has awarded its highest honor, **honorary membership**, to **Gary J. Klein**, executive vice president and senior principal, Wiss, Janney, Elstner Associates Inc. Mr. Klein received the honor “for improving the safety of infrastructure systems through failure and damage investigations and integrating the lessons learned into building codes.”

Leonard Kleinrock, distinguished professor, Computer Science Department, University of California, Los Angeles, has been awarded the **UCLA Medal**. The medal is given to those with exceptionally distinguished academic and professional achievement and whose work or contributions to society illustrate the highest ideals of UCLA. The campus’ highest honor was presented to Dr. Kleinrock for his remarkable contributions in providing the intellectual foundation for the modern technical age.

Louis J. Lanzerotti, retired distinguished member technical

staff, Bell Laboratories, Alcatel Lucent, and distinguished research professor, Department of Physics, New Jersey Institute of Technology, has been awarded the American Institute of Aeronautics and Astronautics (AIAA) **2020 James A. Van Allen Space Environments Award**. The award recognizes “outstanding contributions to space and planetary environment knowledge and interactions as applied to the advancement of aeronautics and astronautics.” Dr. Lanzerotti receives the award for his “significant contributions to our understanding of the space environment of the Van Allen radiation belts and leadership in establishing societal awareness of space weather.”

Asad M. Madni, independent consultant and retired president, chief operating officer, and CTO, BEI Technologies Inc., received the IEEE Aerospace and Electronic Systems Society’s **2020 Industrial Innovation Award** for “seminal contributions in advanced inertial guidance and their successful transition to defense and commercial applications.” Dr. Madni has also been awarded the **2020 Soichiro Honda Medal** by the American Society of Mechanical Engineers “for outstanding leadership in engineering innovations, particularly the development and commercialization of sensors and systems including the revolutionary microelectromechanical systems GyroChip technology for electronic stability control and rollover prevention in passenger vehicles, which has saved countless lives worldwide.”

Ellen Ochoa, retired director and astronaut, NASA Lyndon B. Johnson Space Center, has been elected **chair of the National Science Board**. Her 2-year term began

May 11. The NSB serves both as the policymaking body of the National Science Foundation and as an independent advisor to Congress and the president on science and engineering and on S&E education policy matters

Ramamoorthy Ramesh, Purnendu Chatterjee Chair in Materials Science and Engineering and Physics, University of California, Berkeley, has been **elected a foreign member of the Royal Society** for his “discoveries in complex oxides, from novel fundamental physics, through new materials, to their application in ferroelectric, magnetic and multiferroic devices.”

J.N. Reddy, distinguished professor, Regents Professor, and Oscar S. Wyatt Jr. Endowed Chair Professor in the J. Mike Walker ’66 Department of Mechanical Engineering, Texas A&M University, received in November 2019 the **Timoshenko Medal** from the American Society of Mechanical Engineers at its annual meeting in Salt Lake City. The medal is considered the most prestigious honor in the field of applied mechanics. Dr. Reddy was recognized for “lifetime contributions to research and education in applied mechanics through the authorship of creative and highly cited papers on variational principles, refined theories of plates and shells, computational methods, and nonlocal theories, which have impacted generations of engineers.” More recently, Dr. Reddy was **elected as a foreign member of the Chinese Academy of Engineering**, a **corresponding member of the Royal Academy of Engineering of Spain**, and an **honorary member of the European Academy of Sciences**. And on April 16, 2020, he was awarded a

2020 SEC Faculty Achievement Award.

Subhash C. Singhal, Battelle fellow emeritus, Pacific Northwest National Laboratory, received the inaugural **Subhash Singhal Award** of the Electrochemical Society. The award was created by the Society's High-Temperature Energy, Materials, & Processes Division to recognize excellence and exceptional research contributions to the science and engineering of solid oxide fuel cells (SOFCs) and electrolyzers (SOECs). The award was presented to Dr. Singhal last September at the 16th International Symposium on Solid Oxide Fuel Cells held in Kyoto.

On April 27 during the annual meeting of the National Academy of Sciences, 12 NAE members were elected to NAS membership:

John F. Brady, Chevron Professor of Chemical Engineering and professor of mechanical engineering, California Institute of Technology; **Marilyn A. Brown**, Regents' and Brook Byers Professor of Sustainable Systems, School of Public Policy, Georgia Institute of Technology; **Vinton G. Cerf**, chief internet evangelist, Google Inc.; **Ronald Fagin**, IBM fellow, IBM Almaden Research Center; **Yonggang Huang**, Walter P. Murphy Professor of Civil and Environmental Engineering, Northwestern University; **Chaitan Khosla**, professor, Departments of Chemical Engineering and Chemistry, Stanford University; **Arunava Majumdar**, Jay Precourt Professor, Department of Mechanical Engineering, and codirector, Precourt Institute for Energy, Stanford Uni-

versity; **Arkadi S. Nemirovski**, John Hunter Chair and professor, School of Industrial and Systems Engineering, Georgia Institute of Technology; **Kimberly A. Prather**, distinguished professor and distinguished chair in atmospheric chemistry in the Department of Chemistry and Biochemistry and at Scripps Institution of Oceanography, University of California, San Diego; **Jennifer Rexford**, Gordon Y.S. Wu Professor in Engineering, Princeton University; **Samuel I. Stupp**, board of trustees professor of materials science, chemistry, medicine, and biomedical engineering, and director, Simpson Querrey Institute for BioNanotechnology, Northwestern University; and **Jeffrey D. Ullman**, Stanford W. Ascherman Professor of Computer Science Emeritus, Stanford University.

NAE Chair, Home Secretary, and Councillors Elected

This spring the NAE elected a new chair and home secretary, reelected two incumbent councillors, and elected two new councillors. All terms begin July 1, 2020.

Elected to a 2-year term as NAE chair was **Donald C. Winter**, independent consultant, professor of engineering practice at the University of Michigan, and former secretary of the Navy. Elected to a 4-year term as NAE home secretary was **Carol K. Hall**, Camille Dreyfus Distinguished University Professor in the Department of Chemical and Biomolecular Engineering at North Carolina State University.

Katharine G. Frase, retired vice president of education business development at International

Business Machines Corporation, and **Yannis C. Yortsos**, dean of the Viterbi School of Engineering at the University of Southern California, were reelected to 3-year terms as councillors. Newly elected to 3-year terms as councillors were **Anjan Bose**, Regents Professor in the School of Electrical Engineering and Computer Science at Washington State University, and **Brenda J. Dietrich**, Arthur and Helen Geoffrion Professor of Practice at Cornell University and retired vice president of International Business Machines Corporation.

On June 30, 2020, **Gordon R. England**, chair of PFP Cybersecurity, will complete two terms of service as NAE chair, the maximum allowed

under the Academy's bylaws. **Julia M. Phillips**, retired vice president and chief technology officer at Sandia National Laboratories, will complete a 4-year term of service as home secretary. **Frances S. Ligler**, Lampe Distinguished Professor of Biomedical Engineering at North Carolina State University/UNC-Chapel Hill and retired senior scientist at the US Naval Research Laboratory, and **H. Vincent Poor**, Michael Henry Strater University Professor at Princeton University, will complete 6 continuous years of service as councillors, the maximum allowed under the Academy's bylaws. They were recognized in May for their distinguished service and other contributions to the NAE.



Donald C. Winter



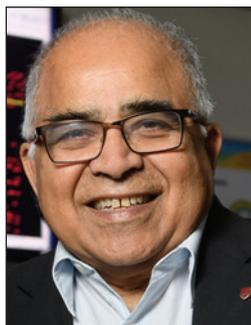
Carol K. Hall



Katharine G. Frase



Yannis C. Yortsos



Anjan Bose



Brenda J. Dietrich



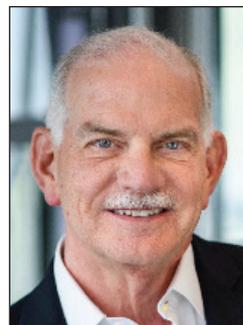
Gordon R. England



Julia M. Phillips



Frances S. Ligler



H. Vincent Poor

NAE Honors 2020 Draper Prize Winners

The NAE's Charles Stark Draper Prize honors an engineer whose accomplishment has significantly impacted society by improving quality of life, providing the ability to live freely and comfortably, and/or permitting access to information. The 2020 award winners were honored at a black-tie dinner

February 19 at the National Academy of Sciences in Washington. The recipients accepted their award before an audience of more than 75 guests, with NAE president **John L. Anderson** at the podium. Also assisting in the presentation was Ken M. Gabriel, president and CEO of Draper.

Charles Stark Draper Prize for Engineering

Jean Fréchet and **C. Grant Willson** were recognized "for the invention, development, and commercialization of chemically amplified materials for micro- and nano-fabrication, enabling the extreme

miniaturization of microelectronic devices.”

The chemically amplified resist (CAR) materials created by Drs. Fréchet and Willson are used in lithography to form the minute structures that make up today’s semiconductor devices. They are involved in the manufacture of nearly all the microprocessors and memory chips that enable electronic devices such as personal computers, mobile phones, and motor vehicles.

At the time of the invention of CAR materials, the semiconductor industry was approaching a limit. The existing lithography process and resist materials used in the fabrication process could not form the smaller images required to continue improving devices. High-resolution light with shorter wavelengths was preferred, but such light sources were very weak in output in those days. Drs. Willson and Fréchet developed a method of chemically amplifying resist materials to provide higher sensitivity, which improved production efficiency by reducing photo irradiation time for image formation and enabled the production of much smaller structures.

Jean Fréchet is an expert in polymers, well known for his work

on dendrimers, separation media, polymer therapeutics, and other technologies. His work has garnered over 120,000 citations (Google Scholar). After retiring from the University of California, Berkeley, he joined the newly created King Abdullah University of Science and Technology (KAUST) in 2010 as its first vice president for research; he retired in January 2019 as senior vice president for research, innovation, and economic development. A member of the NAE and NAS, Dr. Fréchet has been selected for numerous honors, including the American Chemical Society (ACS) Arthur C. Cope Award, the Academia Europaea’s Erasmus Medal, the French Grand Prix de la Maison de la Chimie, the Japan Prize (shared with Dr. Willson), and the King Faisal International Prize in Chemistry. He received his BS in chemical engineering from the Institut de Chimie et Physique Industrielles, and his MS and PhD in polymer chemistry from both the State University of New York College of Environmental Science and Forestry and Syracuse University.

C. Grant Willson is a professor of chemical engineering and chemistry at the University of Texas at

Austin, where he holds the Rashid Engineering Regents Chair. His research, supported by grants from both government and industry, focuses on the design and synthesis of functional organic materials with emphasis on organic materials for microelectronics. He joined the faculty of UT Austin in 1993 after working at IBM for 17 years; when he left he was an IBM fellow and manager of polymer science and technology at the IBM Almaden Research Center in San Jose. Dr. Willson’s research has been recognized with numerous honors: the National Medal for Technology and Innovation (2008), the Japan Prize (2013, shared with Dr. Fréchet), the NAS Award for Chemistry in Service to Society and, from ACS, the Polymer Science, Applied Polymer Science, Chemistry of Materials, and Heroes in Chemistry awards, among others. He is a fellow of ACS, the Materials Research Society, and Society of Photo-Optical Instrumentation Engineers, and a member of the NAE, American Society for Engineering Education, and Society of Petroleum Engineers. He received both his BS and PhD from the University of California, Berkeley, and his MS from San Diego State University, all in organic chemistry.



Left to right: Ken M. Gabriel, Jean Fréchet, C. Grant Willson, and John L. Anderson.

Acceptance Remarks by C. Grant Willson

The organizers of this wonderful event told Jean and me that only one of us could speak because of time limitations. Jean flipped a coin and I won—or maybe I lost. Anyhow, I was chosen by chance.

Sharing the Charles Draper Prize with Professor Fréchet is a huge and unexpected honor. This award is known throughout the world as the Nobel Prize for Engineers. The list of

previous winners certainly includes many of the most famous engineers and scientists and it is hard to imagine that we might be included in such a list. It is also humbling to know that there are so many friends out there who were willing to devote time and energy to the myriad nomination forms and support letters, etc., that had to have been generated in our behalf. We offer our most sincere thanks to those people. We also thank the members of the committee that analyzed these documents and ultimately chose to honor Professor Fréchet and me. We offer special thanks to Janet and Debbie, our wonderful wives, and to our sons for their tolerance of the long days and many absences from home that were required to do the work that is being honored.

The work that led to the discovery that is being honored was inspired by a need to continue improving the function and reducing the cost of IBM's semiconductor products. In the early 1980s IBM was manufacturing more semiconductor devices than anyone in the world and we were dedicated to keeping up with Moore's Law, which predicts a doubling of the number of devices on each chip every two years. This was always accomplished by finding some way to make the individual devices smaller and smaller. The rate of that device shrinking was sustained for several decades and led to the increase in performance and reduction in price that was responsible for the rapidly growing influence of computers in everyday life.

In the early 1980s, we were stuck. Further shrinking of the devices demanded printing with shorter-wavelength ultraviolet light. The light sources that were available did not produce much light at the

shorter wavelength, so efficient printing required materials that were orders of magnitude more sensitive and supported higher-resolution patterning than any that were available. Luckily, at that time Professor Fréchet, who was then at the University of Ottawa, chose to come to the IBM Research Laboratory for a sabbatical leave. We started a collaboration and a friendship that has lasted over 40 years and produced more than 50 joint papers and patents. Jean and his family are very close friends and he is the godfather of my youngest son, Andrew, who is here tonight.

When Jean arrived at IBM we discussed the fact that the industry was stuck for want of a new imaging material and out of those discussions came the original design for the acid-catalyzed or "chemically amplified" resists. We explored several polymer platforms for such systems and managed to demonstrate the concept before Jean returned to Ottawa, where he continued to work with me from a distance. In order to make faster progress in his absence, I sought out and hired a terrific postdoctoral student from the same group where Jean earned his PhD, that of Prof. Conrad Schuerch. This student's name was Hiroshi Ito. Hiroshi was an incredibly productive and clever chemist and the collaboration of the three of us made rapid progress.

In 1985 we sent the first liter of chemically amplified resist to Burlington, Vermont, for evaluation in manufacturing and it was quickly implemented. Standing in the clean room at Burlington and watching huge numbers of parts being manufactured with our new material and knowing that this material enabled IBM to lead the world in chip pro-



C. Grant Willson

duction was a thrill that is difficult to describe and one that I will surely never forget.

The basic design of the resists that are in use to make all the advanced devices in the world today is derived from that early work. Of course, the materials have evolved and improved tremendously, in significant part due to the work of Dr. Ito, who became a permanent employee of IBM and worked on these materials for his entire career. He was ultimately appointed an IBM fellow in recognition of his accomplishments. Sadly, we lost Dr. Ito in 2009, but the legacy of his effort remains. I feel sure that if he were still with us, he would have been included in this award.

Jean and I both will treasure the Draper Prize. It will continuously remind us how lucky we were to be able to work in laboratories as efficient and well equipped as those provided by IBM. It will also remind me how lucky I was to get to work with people as wonderful as Jean and Hiroshi. I am a very lucky and very grateful man! I know that Jean is too. Thank you!

NAE Director of Programs Elected to AIMBE College of Fellows

Congratulations to Guru Madhavan, NAE program director and Norman R. Augustine Senior Scholar, on his election to the American Institute for Medical and Biological Engineering (AIMBE) College of Fellows. AIMBE is a nonprofit, honorific society of the most accomplished individuals in the fields of medical and biological engineering. Its mission is to advocate for biomedical engineering innovation through public policy initiatives.

AIMBE fellows are peer-nominated, peer-reviewed, and peer-elected by outstanding medical and biological engineers who include Nobel laureates, Presidential Medal winners, and members of the National Academies. Guru was inducted during the AIMBE Annual Event March 29–30 at the National Academy of Sciences.

Please join us in congratulating Guru. You can reach him at GMadhavan@nae.edu.



Guru Madhavan

Calendar of Meetings and Events

August 5–6 NAE Council Meeting
via Zoom

October 4–5 NAE Annual Meeting
via Zoom

Would you like to support the NAE both now and in the future?

A donor-advised fund (DAF) enables you to manage your charitable giving simply and efficiently.

DAFs offer the following benefits:

-  They simplify the administrative burden of fulfilling your philanthropic objectives.
-  They offer tax advantages of giving directly to the NAE with added flexibility around the timing of gifts.
-  They may be a more tax- and cost-efficient alternative to a private foundation.

Learn more about ways to give at
www.nae.edu/waystogive

In Memoriam

ARCHIE R. CLEMINS, 76, president, Caribou Technologies Inc., died March 14, 2020. Admiral Clemens was elected in 2006 for the creation and initial fielding of the US Navy's transformational use of information, which has enabled net-centric operations.

JOHN F. DAVIDSON, 93, professor emeritus, University of Cambridge, died December 25, 2019. Professor Davidson was elected a foreign member in 1976 for leadership in performing experimental and theoretical studies in fluidization and their applications to engineering practice.

DANIEL W. DOBBERPUHL, 74, independent consultant, died October 26, 2019. Mr. Dobberpuhl was elected in 2006 for the innovative design and implementation of high-performance, low-power microprocessors.

IRWIN DORROS, 89, president, Dorros Associates, died June 22, 2019. Dr. Dorros was elected in 1990 for leadership in the development of public telephone networks, integrated services digital networks (ISDN), and management of major telecommunications research.

ROBERT M. DRAKE JR., 99, vice president, research development, Combustion Engineering Inc., died February 20, 2020. Dr. Drake was elected in 1974 for contributions to research in heat transfer in rarefied gases at high velocities and to engineering education.

MICHAEL J. FETKOVICH, 86, Phillips Fellow emeritus, Phillips Petroleum, died February 3, 2020. Dr. Fetkovich was elected in 2005 for the development of widely used techniques for determining future oil and gas production and recoverable reserves.

BARRIE GILBERT, 82, director, NW Labs, Analog Devices Inc., died January 30, 2020. Dr. Gilbert was elected in 2009 for advancement of high-speed analog microelectronics.

THOMAS S. HUANG, 83, William L. Everitt Distinguished Professor of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, died April 25, 2020. Dr. Huang was elected in 2001 for contributions to the theory and practice of image compression, retrieval, and analysis.

MICHEL HUG, 89, consultant, Design Stratégique SARL, died December 19, 2019. Dr. Hug was elected a foreign member in 1979 for contributions and leadership in engineering research in hydraulics as applied to power stations and in planning and execution of the nuclear power plant program of France.

GEORGE E. KELLER II, 86, chief engineer, Mid-Atlantic Technology, Research and Innovation Center, died October 7, 2019. Dr. Keller was elected in 1988 for invention and insightful analysis of novel separation processes.

SUNG WAN KIM, 79, distinguished professor of pharmaceuticals and pharmaceutical chemistry and bioengineering, University of Utah, died February 24, 2020. Dr. Wan Kim was elected in 2003 for the design of blood-compatible polymers with human applications, including drug-delivery systems.

CHARLES E. KOLB, 74, president and chief executive officer, Aerodyne Research, Inc., died January 20, 2020. Dr. Kolb was elected in 2013 for instruments that advanced measurements of air pollution and aerosols.

ROBERT M. NEREM, 82, Institute Professor and Petit Professor Emeritus, Institute for Bioengineering and Bioscience, Georgia Institute of Technology, died March 5, 2020. Dr. Nerem was elected in 1988 for biomedical engineering leadership through major contributions to the understanding of dynamics of blood flow and blood vessels in health and disease.

MARC S. NEWKIRK, 72, president, Lightfield Foundation, died November 25, 2019. Mr. Newkirk was elected in 1997 for invention and development of novel processes for manufacture of ceramic and metal matrix composites.

WALTER L. ROBB, 91, president, Vantage Management Inc., and retired senior vice president, GE Corporate Research and Development Center, died March 23, 2020. Dr. Robb was elected in 1982 for

applications of high technology to the health and medical needs of the world community.

LANNY D. SCHMIDT, 81, professor of chemical engineering and materials science, University of Minnesota, died March 27, 2020. Dr. Schmidt was elected in 1994 for the application of principles of surface science to the design of new catalytic

cycles and the molecular understanding of catalytic reaction engineering.

PHILIP C. SINGER, 77, professor emeritus, University of North Carolina at Chapel Hill, died February 17, 2020. Dr. Singer was elected in 1995 for contributions to the treatment of public water supplies and to the education of environmental engineers.

JOHN F. WELCH JR., 84, executive chair, Jack Welch Management Institute, and retired chair and chief executive officer, General Electric Company, died March 1, 2020. Mr. Welch was elected in 1983 for leadership in developing engineered plastics and for increasing national recognition of the importance of technology and innovation.



NATIONAL ACADEMY OF ENGINEERING

The CARES Act and You

Consider the new legislation when making your gift.



Charitable IRA Rollover Changes

The CARES Act has suspended required minimum distributions (RMDs) for 2020, but those who are 70½ or older can still make charitable IRA rollover gifts to the NAE of up to \$100,000 from a traditional IRA. In 2020 such gifts will not substitute for a donor's RMD since there is no requirement to withdraw.



Universal Charitable Deduction

Tax filers—whether single or joint—will be able to deduct up to \$300 in charitable gifts of cash in 2020, even if they don't itemize deductions.



Suspension of Adjusted Gross Income (AGI) Limitations

Before passage of the CARES Act, the charitable deduction for a gift of cash was limited to 60% of a donor's adjusted gross income. In 2020, the same gift can help reduce a donor's tax liability up to 100% of that donor's adjusted gross income. Charitable deductions resulting from charitable gift annuities funded with cash also qualify for the 100% of AGI rule.

Learn more about planned giving at
www.nationalacademiesgiving.org



Invisible Bridges

Interface Value



Guru Madhavan is the Norman R. Augustine Senior Scholar and director of NAE programs.

Being at sea is perilous. Any safety feature on a ship can backfire. Lew had known that well since his Navy days—he spent long deployments in the Western Pacific during the Vietnam conflict. Later, he worked in corporate public relations building a career in crisis management. Then he found himself in a crisis.

In March 2019 Lew, in his 70s, and his wife set off to Norway for a 13-day cruise, *In Search of the Northern Lights*. The *Viking Sky* was fairly small by cruise ship standards—on this trip it carried 915 passengers and 458 crew members—but that’s how Lew wanted it. “Those big vessels are not a very pleasant experience. You’re herded around like cattle,” he told me.

The *Viking Sky* was Italian-built in 2017, steel, 228 meters long, 47,800 tons, and powered by four diesel generators. After a routine tour circuit, the ship would leave Bergen, motor up the Norwegian coast to the north of the Arctic Circle, then return to Stavanger and England.

Everything went according to plan. Aurora Borealis – check. Tirpitz Museum – check. Sami camp – check. Reindeer sleigh ride – check.

Late in the morning on March 23, the next to last day of the cruise, Lew was relaxing in his cabin. The next several minutes changed his life.

The ship began rolling violently, tilting almost 45 degrees. Waves rose up to 30 feet. Lew was thrown across the room. Then he hurtled head-first into a chair

against the far wall. “I heard a kind of sickening crunch in my neck.” He felt woozy. “I don’t know whether I blacked out but the next thing I vividly remember is I kind of rolled over onto my back and I couldn’t move my right arm. It was paralyzed.... I couldn’t feel anything.”

The *Viking Sky* had sailed into Hustadvika, a region notorious for dangerous storms and hollow breaking seas. Rough waters were expected there. But something else had happened.

During the violent movements, the automated sensors on the generators picked up low levels of lubricant oil. Assuming depletion, the sensors sent alarms and automatically tripped the engines, causing a blackout.¹ Propulsion was lost. The captain couldn’t restart the engines and, because the ship had no controls, couldn’t navigate through the dangerous conditions. Tables and pianos skidded. Furniture and people collided. Ceiling panels fell. Icy sea water poured in. Passengers screamed for help. Distress videos were tweeted.

One of Lew’s fellow passengers later recalled: “I grabbed my wife but I couldn’t hold on. She was thrown across the room, and then she got thrown back again....” He added: “I did not have a lot of hope. I knew how cold that water was.... You would not last very long. That was very, very frightening.”²

The captain made a mayday call around 2:00 pm. The waves and winds ruled out the option of lifeboats. Fortunately, a rescue helicopter arrived promptly. Over the next 20 hours, the helicopter hoisted one person every couple of minutes, successfully evacuating 479 passengers. The next day the conditions calmed. The ship, with the remaining passengers, was tugged to the Norwegian shore town of Molde.

Lew was already in intensive care.

*

¹ Accident Investigation Board Norway, *On the Investigation into the Loss of Propulsion and Near Grounding of Viking Sky, 23 March*, Lillestrøm, Norway, November 12, 2019.

² Cristina Abellan Matamoros, *Euronews*, March 24, 2019, <https://tinyurl.com/yysm89kp>.

The *Viking Sky* was a near disaster. The sensors worked to specification—if the oil level was lower than a threshold, they were supposed to turn off the power to protect the engine. But the oil was actually within the specified levels: the rolling of the ship caused the sensors to be briefly exposed to air, leading to their false reading.

Think of a fuel gauge wrongly “assuming” that a car going uphill is running out of fuel and, without knowing the operating context, automatically shutting down both the driver’s controls and the car. This kind of narrow logic proved harmful to the ship and its passengers.

Most failures in engineering—and by extension, organizations—share this quality: a local safety function doesn’t “know about” the broader safety strategy, a unit by design protects only itself or serves only the adjacent component without appreciating the overall system.

Imagine the catastrophe if the human nervous system worked this way. Our bodies send signals that switch and tune a multitude of responses, such as fear, fever, pain, nausea, or anxiety. These might be called the *face value* of safety. Sometimes these are overexpressions of defense honed by natural selection. Evolutionary biologist Randolph Nesse likens these effects to how smoke detectors react to changes in the indoor environment—sometimes they go off even when there is no danger.

*We accept certain
false alarms because
they typically don’t cost
much, or anything.*

We accept certain false alarms because they typically don’t cost much, or anything. A parallel could be drawn to the availability of cheap, overreactive automation. “Birds flee from backyard feeders when any shadow passes overhead,” Nesse notes. “Wearing a seatbelt is unnecessary 999 times out of 1000, but sensible people do it.”³

Yet the cost of the convenience may in some sense far exceed the benefits of the convenience. The preponderance of overresponsive automation could make

³ Nesse R. 2005. Natural selection and the regulation of defenses: A signal detection analysis of the smoke detector principle. *Evolution and Human Behavior* 26(1):88–105, p. 98.

us psychologically more averse to risk—call it the *interface value* of safety.

The *Viking Sky* incident illuminates the consequences of excessive faith in automation. In the so-called “user-centered” design, the “users”—the ship’s crew—had no control. Protecting the engines was a critical requirement, but there was no option to override the erroneous automatic response that resulted in a calamitous shutdown. The extent of the harm and distress could have been avoided.

The *Viking Sky* crew had every reason to expect that their new ship would continue to perform in bad weather. They had no information that would suggest that the rolling of the ship would cause a total loss of power.

This and similar occurrences are not one-off events. Automation has produced unintentional acceleration or poor antilock braking in cars. Aircraft pilots have found themselves unable to control maneuvering after takeoff or to override the software takeover of flight controls and prevent a sudden dive. Such “automation surprises” are matters of life and death. The interface value of safety also brings to light deficiencies repeated in a typical design and business attitude that ties automation with revenue.

Whether a sensor’s actions were right or wrong in these situations, or objective safety is a pure illusion, is worth discussion. Again, the sensors and “fail-safe” they were connected to performed as they were intended to. The fault was in not imagining a circumstance where humans would know better than machines. As a result, a point failure launched a cascade that took down the entire system and even, in some cases, the people who had trusted those systems.

Responsible engineering knows that safety exists beyond official statistics and codes. Every engineered system we engage with has the potential for “behavioral surprises” even in the most quantifiable environments, even when devoid of human actions. Safety can and does thrive at its subjective best, akin to excessive belief in hand sanitizers to curb a viral pandemic. The face value of safety may well depend on its interface value.

*

When Lew yelled for help after being injured, six crew members stabilized his neck, took him on a stretcher five floors down from his room for medical attention, and later eight floors up to the helipad for rescue. “These guys really worked their tails off to get me there.”

Lew's C1 and C2 vertebrae were shattered in the collision and the supporting ligaments ripped. He endured a complex surgery. Two titanium rods were inserted with several screws to reconnect his skull and neck. His rehab was intense, his recovery slow. "I cannot turn my head at all, either up-down or sideways," he said. "That's what I'll live with for the rest of my life. I feel very lucky...actually. It could have been much, much worse." If the crew of the *Viking Sky* hadn't been well trained, Lew said, "there's an almost endless list of worse things that could have happened." The ship could have run aground on the rocks, resulting in deaths.

It requires a high degree of professionalism and an intense amount of training to operate any ship safely in the ocean, particularly in stormy weather. But, at the same time, the captain and the ship's officers and crew are relying on the technology to do what it's supposed to do. And in this case, technology as a support system failed, not the crew. Humans were the backup. "I hold no ill will toward the ship, or the captain, or the cruise line," Lew said. "I do hold a fair amount of ill will toward the people who made that design decision. I don't know who they are, but I wish they'd done their job better."

The BRIDGE

(USPS 551-240)

National Academy of Engineering
2101 Constitution Avenue NW
Washington, DC 20418

Periodicals
Postage
Paid

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.

www.national-academies.org