National Aeronautics and Space Administration

A Vision for Sustainable Aviation: The Need, Technology Options, and Implications

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Topics

- Vision
- Needs
- Options
- Implications
- Concluding Remarks

VISION for Sustainable Aviation

- Aviation system grows to meet demand
  and improves quality of life for more people worldwide

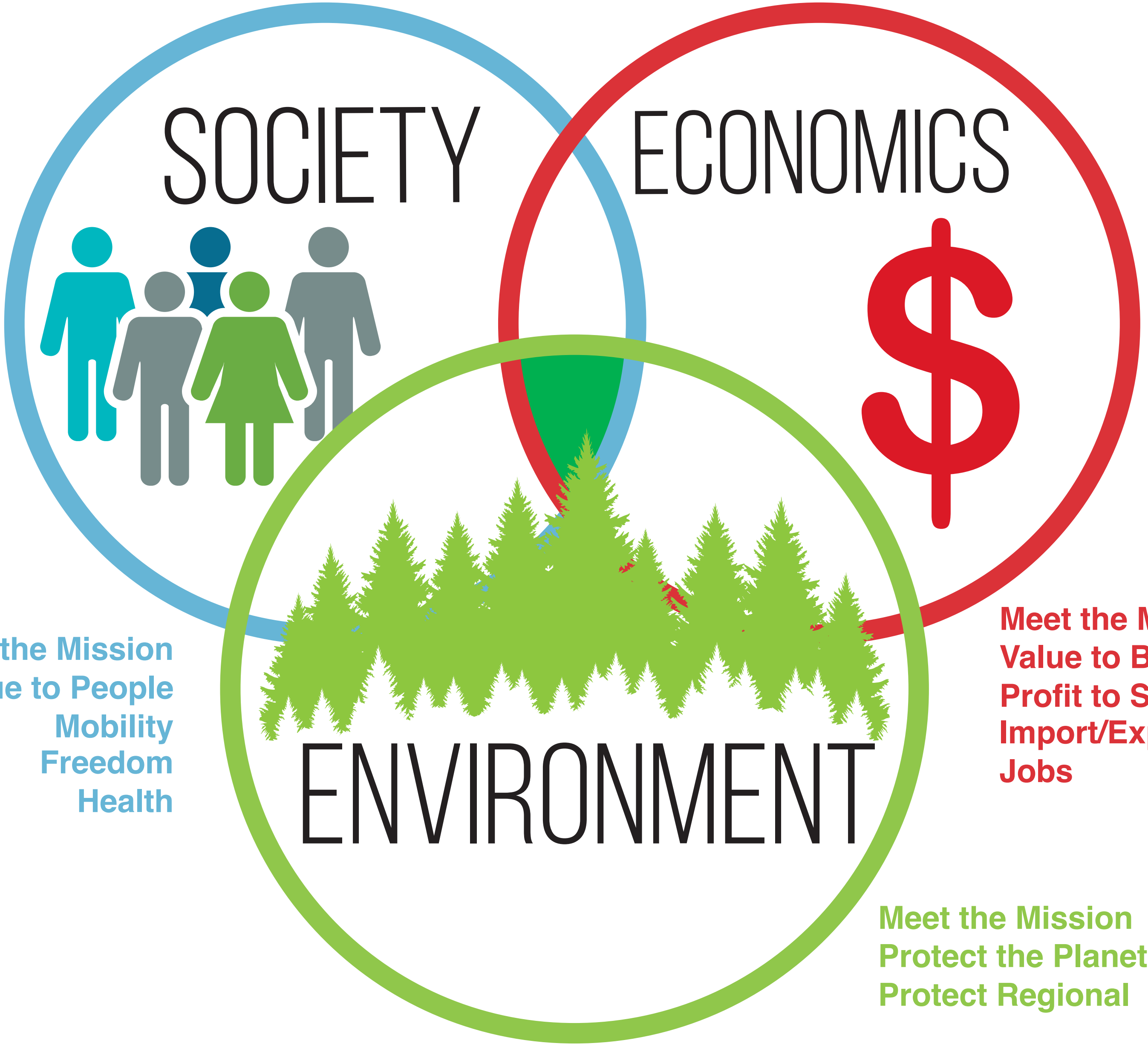
- Aviation is broadly recognized for its value to society
  and as environmentally friendly

- Aviation is safe, clean, quiet, efficient, economical, operable, marketable

- Subsonic commercial airliners remain the 24/7 global backbone
  of domestic and international long-haul air transportation
  and are the key to a sustainable aviation future

- Small aircraft provide growing value relative to other modes of transportation at local and domestic regional range while incubating technology for airliners

Sustainability



Meet the Mission
Value to People
Mobility
Freedom
Health

Meet the Mission
Value to Business
Profit to Shareholders
Import/Export Trade Balance
Jobs

Meet the Mission
Protect the Planet
Protect Regional & Local Ecosystems

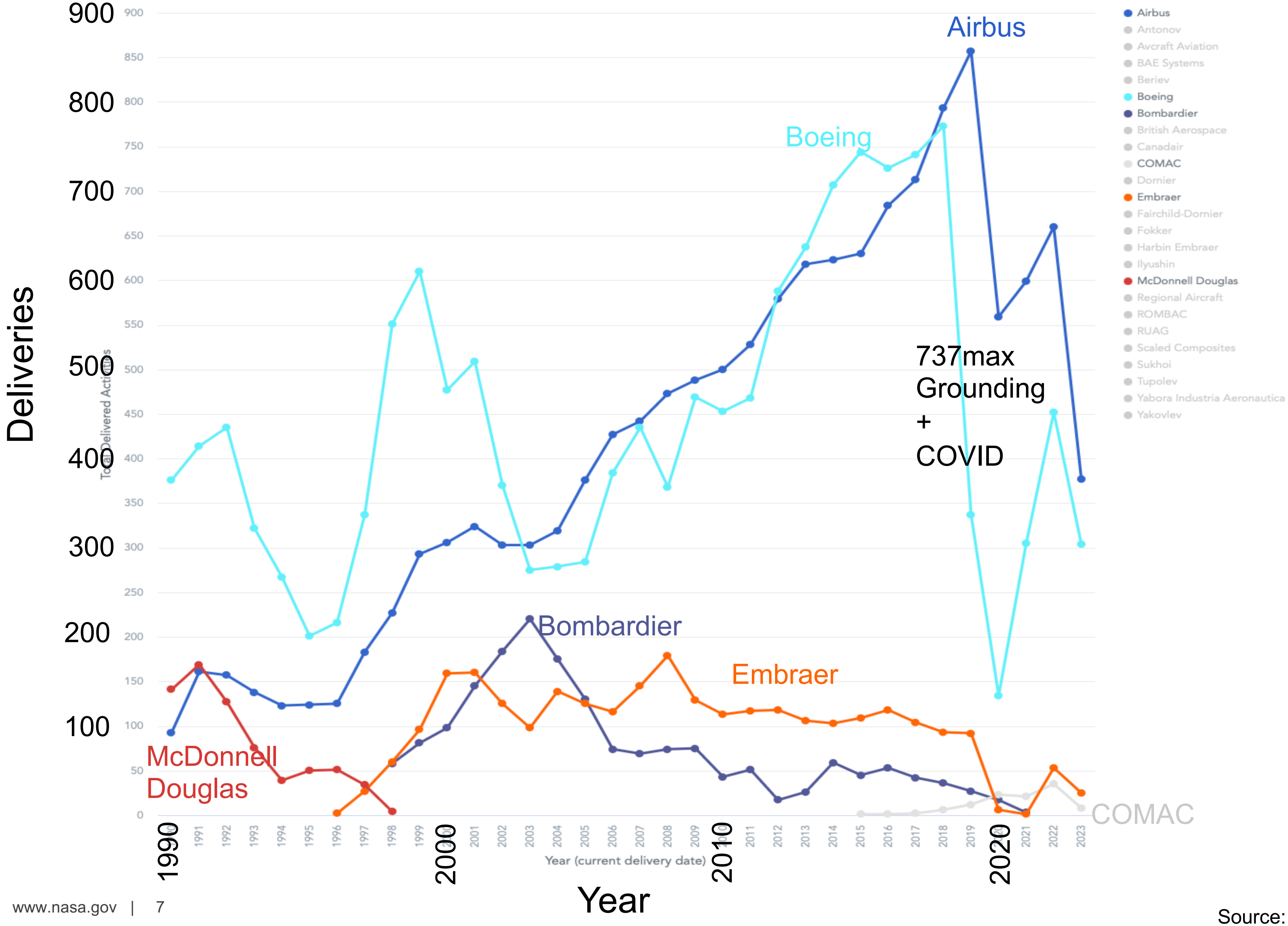
NEEDS for a Sustainable Aviation Future

- Safety – no comprise
- Economics – favorable for entire eco-system, U.S. global competitiveness
- Environmental Friendliness - cleaner emissions, quieter, production, disposal
- Efficient – value of time, value of energy resource, less emissions
- Marketable – value through payload, range, speed, economics, etc.
- Operable – consistent with safe, efficient operations in the global airspace
- Energy future – consistent economy-wide future state
- Timeliness – safely accelerate change, the planet will not wait

Aviation is Vital to our Nation’s Economy

- 8.97 million flights by U.S. carriers worldwide in 2022
- 24 million tons of freight transported by U.S. airlines in 2022
- $1.9 trillion total U.S. economic activity in 2019
- $51.5 billion positive manufacturing trade balance in 2021
- 2.1 million aerospace/defense jobs; 575,000 in aeronautics/aircraft in 2021

Competitiveness (Deliveries) – 1990 to 8/7/2023. (Commercial Jets)



25 companies delivered at least one commercial jet since 1990

Only 5 companies delivered more than 100 commercial jets in a single year

2018 – 6 companies delivered 1728 cum

Boeing leads Airbus through 2002
Close 2003-18, then the Max grounding in 2019, and COVID which effects everyone

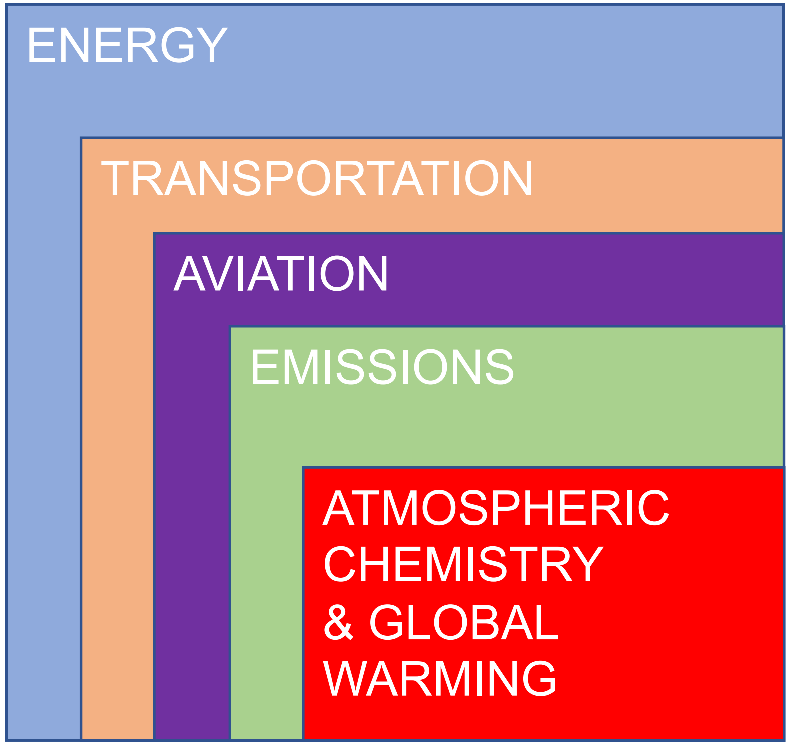
COMAC becoming significant, and further growth anticipated (Chinese market ~20%)

Single-aisle market projected to be ~75% of 40k fleet growth and replacement market over the next 20 years.

Commercial airliner market is extremely difficult to enter.

Source: Aviation Week Network – Fleet Discovery Civil Database 8/7/23

Aviation in Context of Transportation and Broader Energy Economy



Reducing dependence on fossil fuel is the underlying challenge driving change across the entire energy sector

Aviation sector is hard to decarbonize and has unique altitude-based impacts and sensitivity to weight

Subsonic commercial airliner operations dominate aviation's climate impact

Lifecycle impact considerations – "source-to-tank" and "tank-to-wake" plus disposal and local air quality

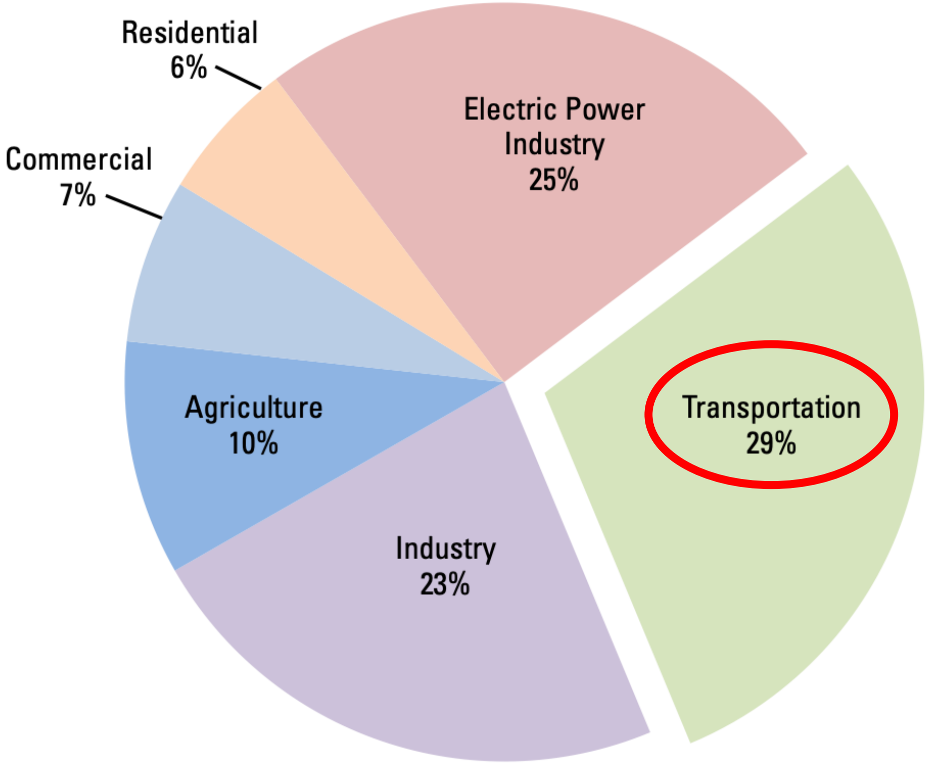
Aviation will need to achieve BOTH net-zero CO_2 emissions and non-CO_2 radiative forcing IN-SECTOR to halt aviation's contribution to global warming. Non-CO_2 impacts comprise two-thirds of the net radiative forcing from aviation.

Motivation (relative to climate change)

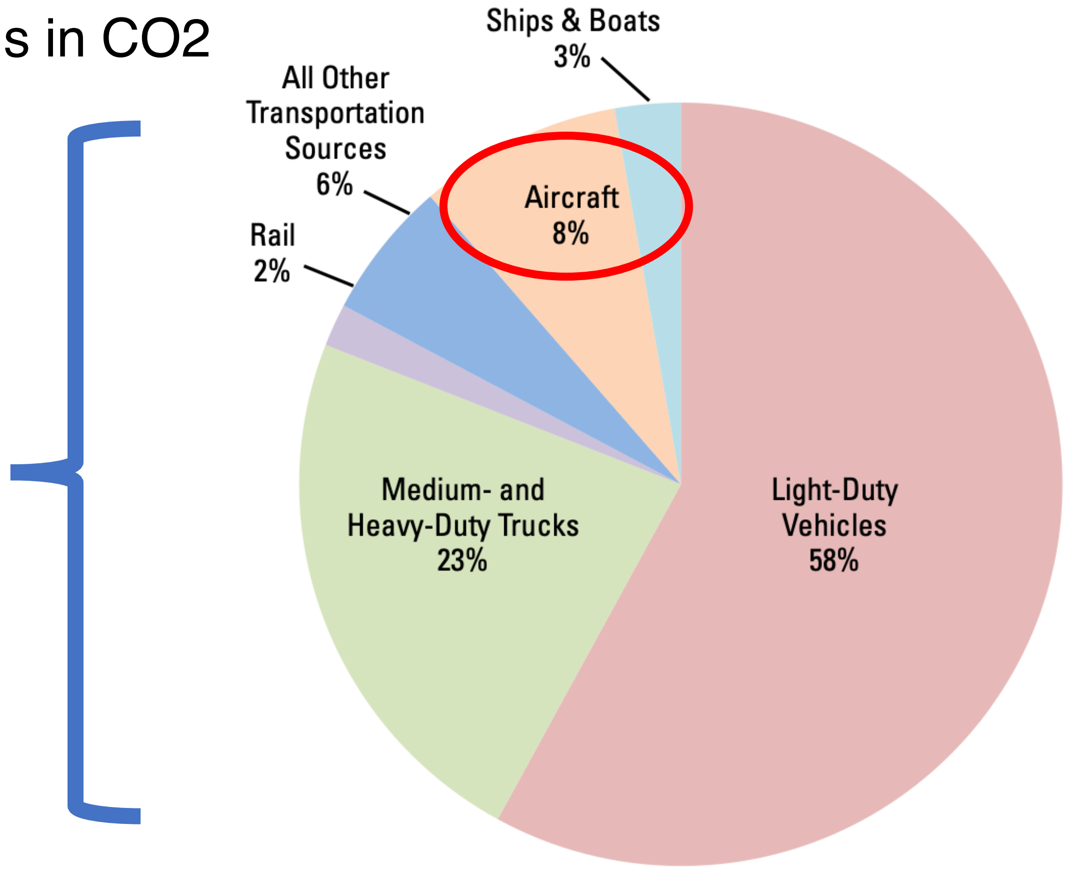
Halt aviation's contribution to global warming
without suppressing flight demand and without out-of-sector offsets
while remaining a viable and valued cornerstone of transportation
(safe, clean, quiet, efficient, operable, economical, marketable)

U.S. Transportation Sector Greenhouse Gas Emissions (GHG) 2021

- Aviation is 8% of Transportation and 2.3% of U.S. GHG Emissions
- 97.3% of Transportation sector GHG Emissions in CO2



Share of U.S. GHG Emissions
by Economic Sector, 2021



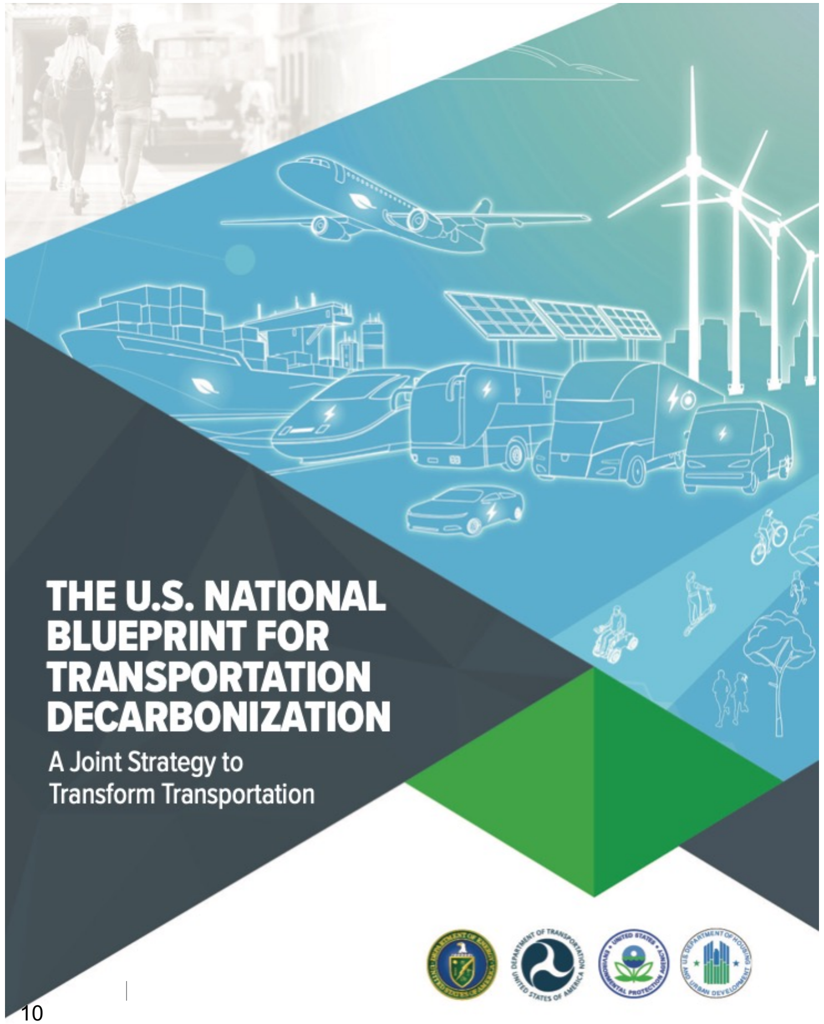
Share of U.S. Transportation Sector
GHG Emissions by Source, 2021

Challenge: hard to decarbonize aviation sector will grow in relative impact over time

Ref: https://www.epa.gov/system/files/documents/2023-06/420f23016.pdf

U.S. National Blueprint for Transportation Decarbonization 2023

- 2019 - Aviation 11% share of U.S. Transportation GHG emissions
- SAF greatest long-term opportunity for Aviation



1 icon represents limited long-term opportunity
2 icons represents large long-term opportunity
3 icons represents greatest long-term opportunity

	BATTERY/ELECTRIC	HYDROGEN	SUSTAINABLE LIQUID FUELS
Light Duty Vehicles (49%)*	3 icons	—	TBD
Medium, Short-Haul Heavy Trucks & Buses (~14%)	2 icons	1 icon	1 icon
Long-Haul Heavy Trucks (~7%)	1 icon	3 icons	2 icons
Off-road (10%)	2 icons	1 icon	1 icon
Rail (2%)	2 icons	2 icons	2 icons
Maritime (3%)	1 icon	2 icons†	3 icons
Aviation (11%)	1 icon	1 icon	3 icons
Pipelines (4%)	2 icons	TBD	TBD
Additional Opportunities	• Stationary battery use • Grid support (managed EV charging)	• Heavy industries • Grid support • Feedstock for chemicals and fuels	• Decarbonize plastics/chemicals • Bio-products
RD&D Priorities	• National battery strategy • Charging infrastructure • Grid integration • Battery recycling	• Electrolyzer costs • Fuel cell durability and cost • Clean hydrogen infrastructure	• Multiple cost-effective drop-in sustainable fuels • Reduce ethanol carbon intensity • Bioenergy scale-up

* All emissions shares are for 2019

† Includes hydrogen for ammonia and methanol

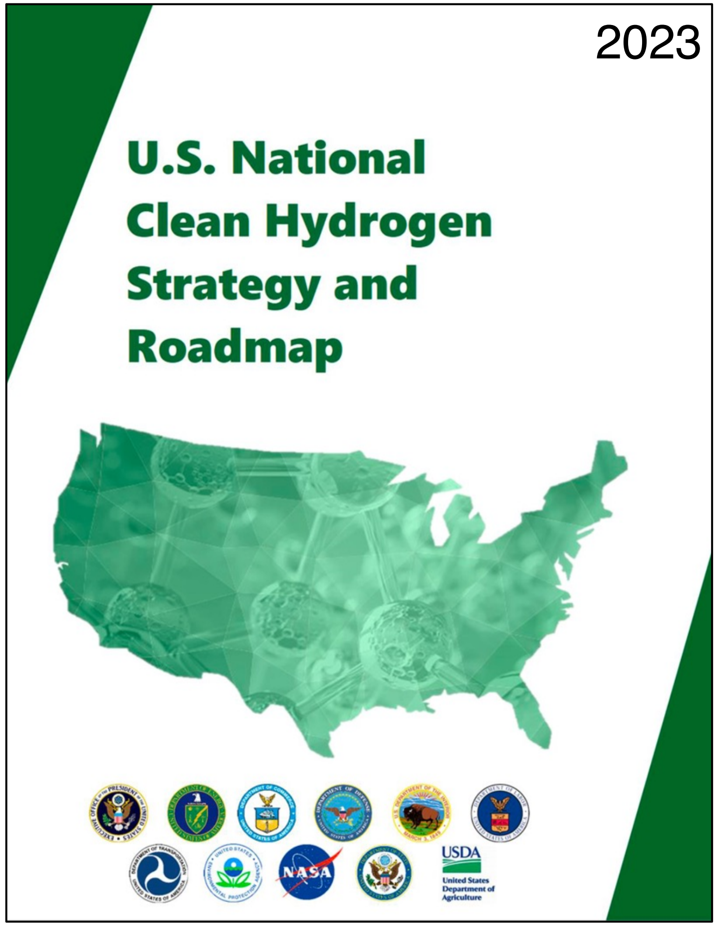
Figure B. Summary of vehicle improvement strategies and technology solutions for different travel modes that are needed to reach a net-zero economy in 2050 (more details provided in Section 5).

Ref: https://www.energy.gov/eere/us-national-blueprint-transportation-decarbonization-joint-strategy-transform-transportation

U.S. SAF Grand Challenge + National Clean Hydrogen Strategy

- 2030: 3B gallons/year
- 2050: 35B gallons/year

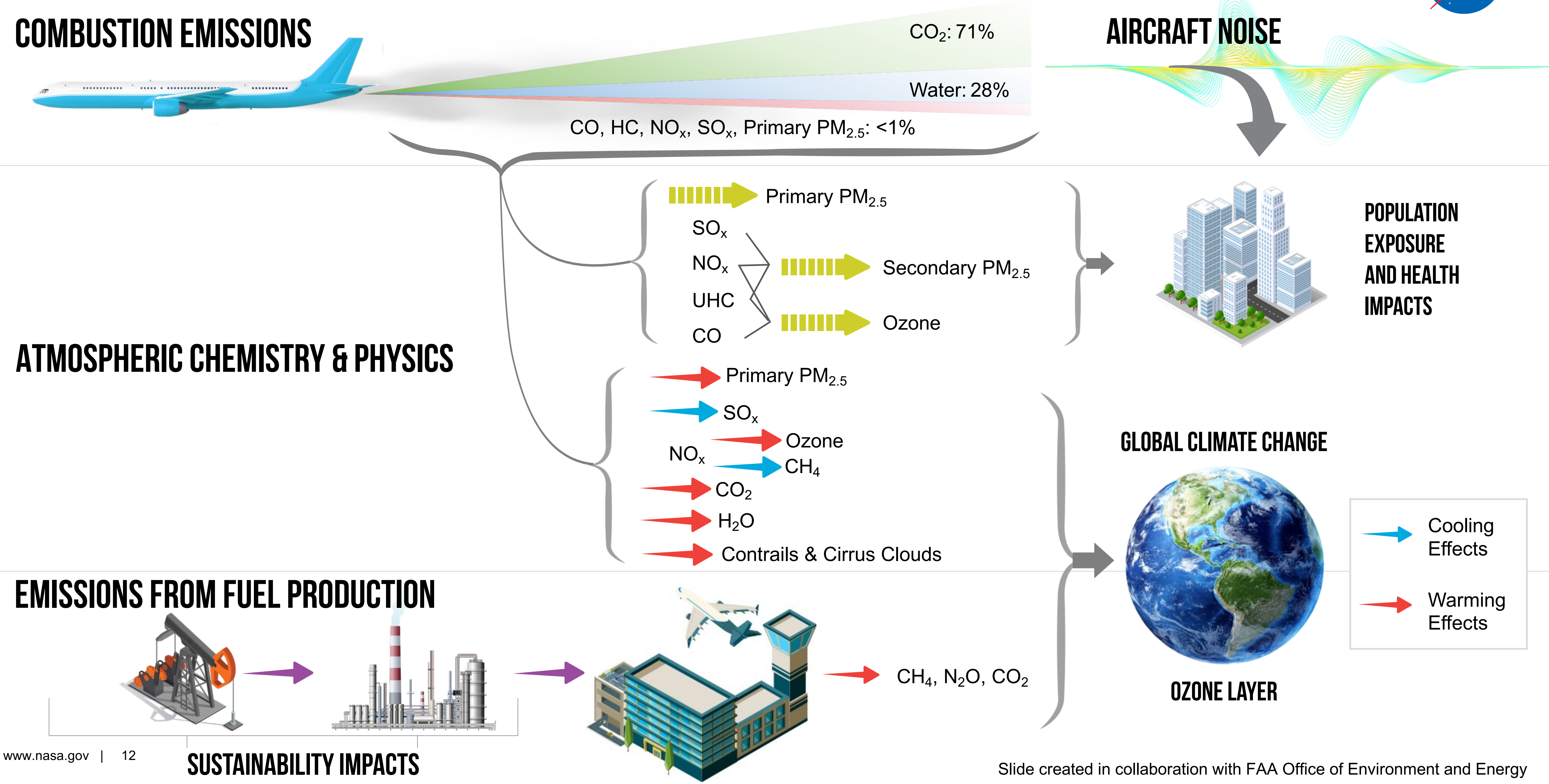
Ref: https://www.energy.gov/eere/bioenergy/sustainable-aviation-fuel-grand-challenge



- 2030: 10 MMT clean H2/year
- 2040: 20 MMT clean H2/year
- 2050: 50 MMT clean H2/year (2-6 MMT/year for SAF)

Ref: https://www.hydrogen.energy.gov/clean-hydrogen-strategy-roadmap.html

Environmental Impacts of Aviation



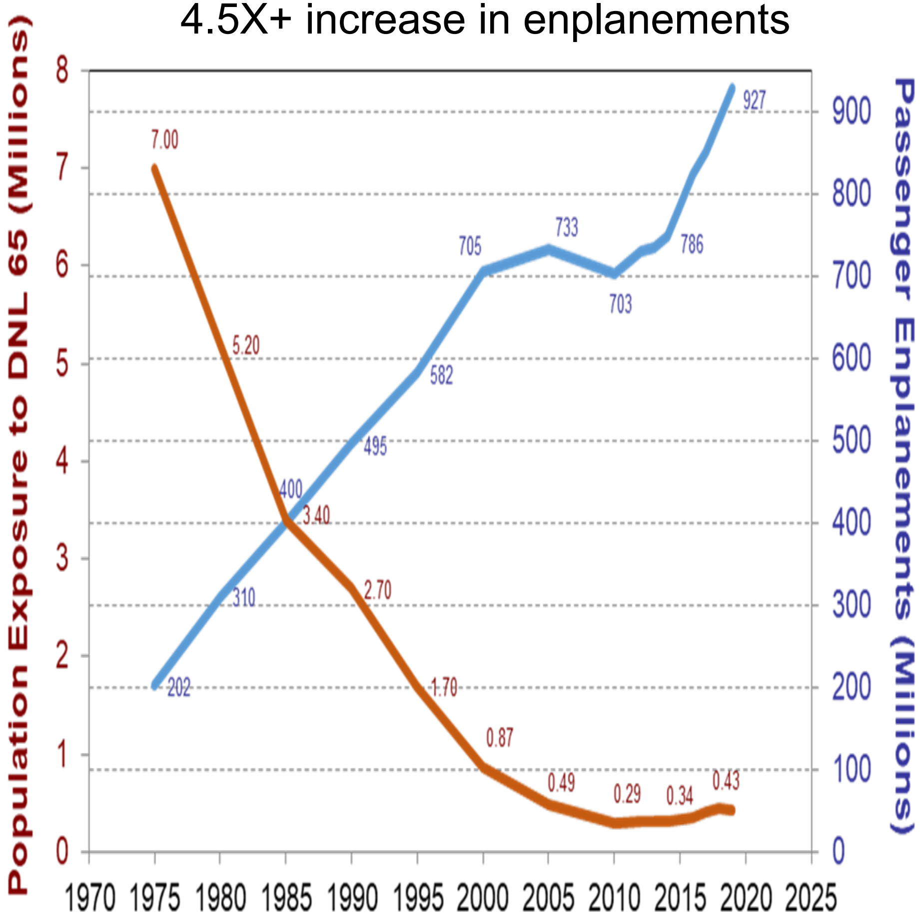
Slide created in collaboration with FAA Office of Environment and Energy

Aviation Noise Impact

Population exposed is a key societal metric dependent on aircraft technology, and number of ops and procedures

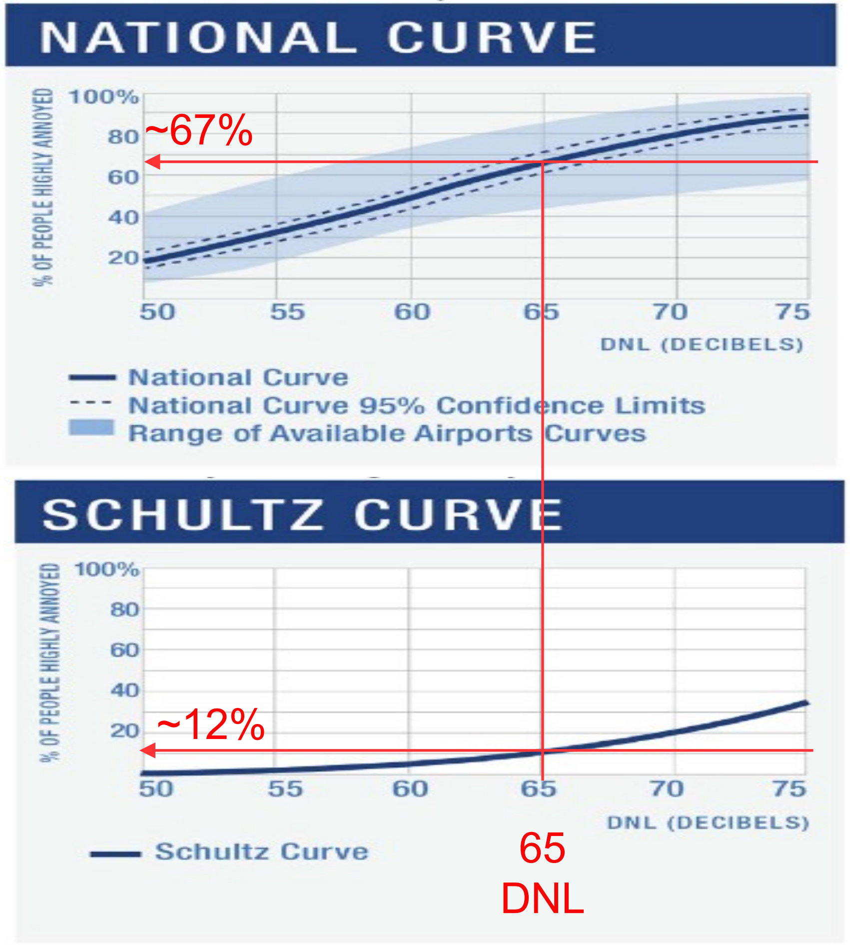
History – FAA Data

90%+ reduction in exposure with 4.5X+ increase in enplanements



FAA Neighborhood Noise Survey 2021

People are significantly more annoyed by 65 dB DNL now than in the 1970s



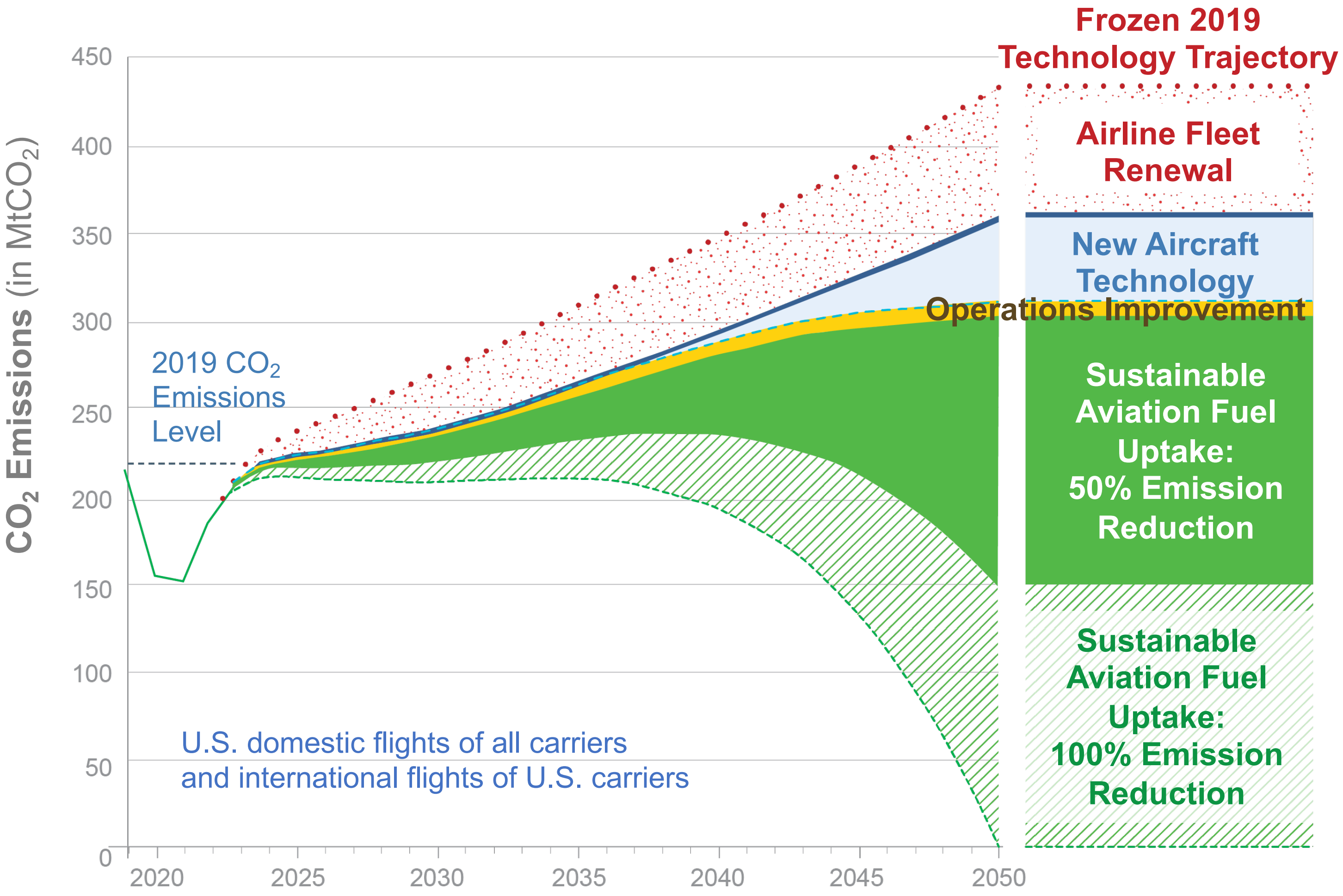
Noise Reduction Remains a Key Environmental Driver

U.S. Aviation Climate Action Plan - 2021

Global Context for Sustainable Aviation

U.S. aviation goal is to achieve
net-zero greenhouse gas emissions by 2050.

U.S. Aviation Climate Action Plan is aligned with
- U.S. economy-wide goal
- International Civil Aviation Organization
- Air Transport Action Group

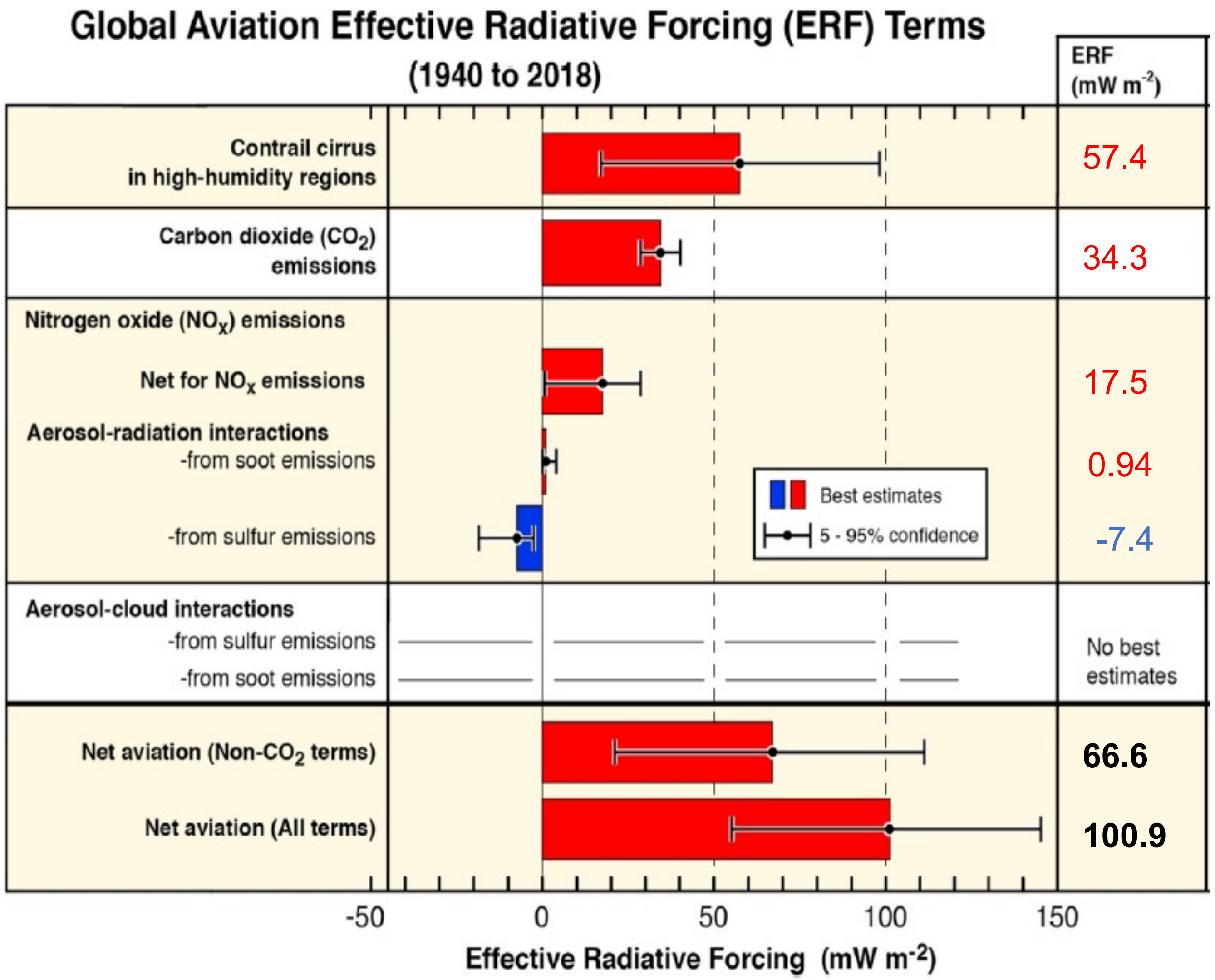


https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf

The U.S. is working with the global community to achieve net-zero greenhouse gas emissions by 2050 using a common basket of measures.

Climate Scientists' View of Aviation Impacts

- Lee et al. (2021) represents latest and most comprehensive assessment of aviation's climate impacts
- Non-CO_2 impacts comprise two-thirds of the net radiative forcing from aviation
- Lot of uncertainty in these estimates. Cruise observational data critically lacking!



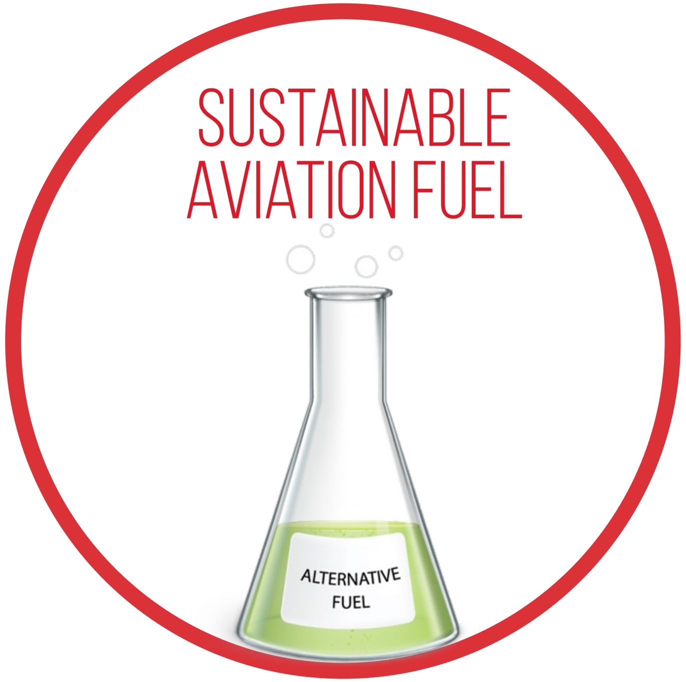
Lee et al. (2021) "The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018" *Atmospheric Environment*, https://doi.org/10.1016/j.atmosenv.2020.117834

"…to halt aviation's contribution to global warming, the aviation sector would need to achieve net-zero CO_2 emissions and declining non-CO_2 radiative forcing ..: neither condition is sufficient alone." Lee et al. (2021)

OPTIONS for Sustainable Aviation (NASA focus)

- Use less energy
  - reduces energy cost
  - reduces required fuel volume
  - airplane & propulsion technology
  - efficient operations
- Use cleaner energy
  - drop-in
  - non-drop-in …requires major change to airplane & infrastructure

NASA = Primary Role



NASA = Supporting Role

NASA = Primary Role

NASA Sustainable Aviation Strategy

2008-2013 | 2014-2019 | 2020-2025 | 2025-2030 | 2030+

Subsonic Concept/Technology Studies
Electrified Aircraft Propulsion
Transonic Truss-Braced Wing
Blended Wing Body

Environmentally Responsible Aviation Project

Flight Demonstrator Studies

Advanced Composites Project

SUSTAINABLE FLIGHT NATIONAL PARTNERSHIP

Sustainable Flight National Partnership to mature and integrate key technologies for next-generation subsonic transports (2030s)

TODAY

ACCELERATING TOWARD NET-ZERO CARBON

Cast a wide net for zero-emission concepts and technologies

Select and develop promising concepts in partnership with universities, industry

Create a credible mission, architecture, and technologies for beyond next-generation subsonic transports for 2050 horizon

POWERING AVIATION TO NET-ZERO CARBON AND BEYOND

Investment in innovation today paves the way to a net-zero carbon and beyond aviation future.

Sustainable Flight National Partnership

Accelerating Toward Net-Zero Greenhouse Gas Emissions and Reduced Non-CO_2 Climate Impact in the 2030s

Advance engine efficiency and emission reduction

Enable integrated trajectory optimization

Advance airframe efficiency and manufacturing rate

Enable use of 100% sustainable aviation fuels

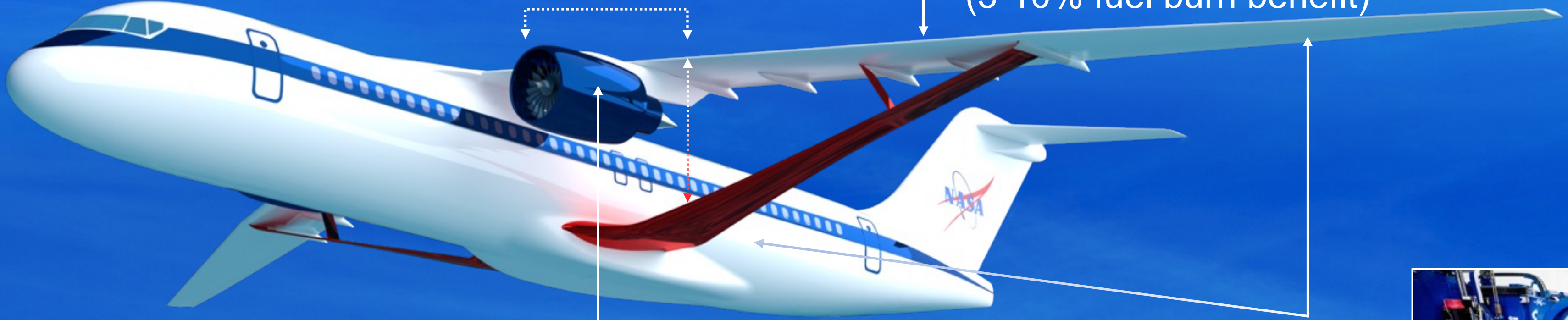
Next-generation transports using up to 30% less fuel, current and future fleets flying optimal trajectories, engines burning sustainable aviation fuels for greater than 50% reduction in lifecycle greenhouse gas emissions

Subsonic Airliner Technologies

Ensure U.S. industry is the first to establish the new “S Curve” for the next 50 years of airliners

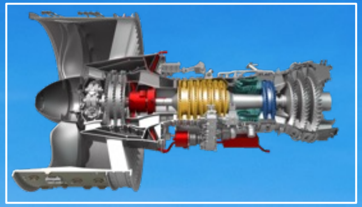
Integrated Aircraft System Efficiency
Propulsion Airframe
Integration Opportunity

Aerodynamic Efficiency
Transonic Truss-Braced Wing
(5-10% fuel burn benefit)



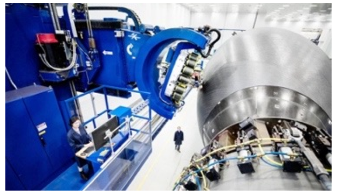
Weight
High-Rate Composites
(4-6x manufacturing increase)

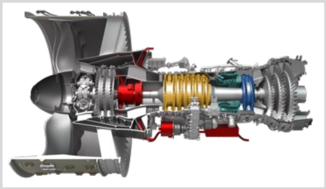
Electrified Aircraft Propulsion
~5% fuel burn and
maintenance benefit

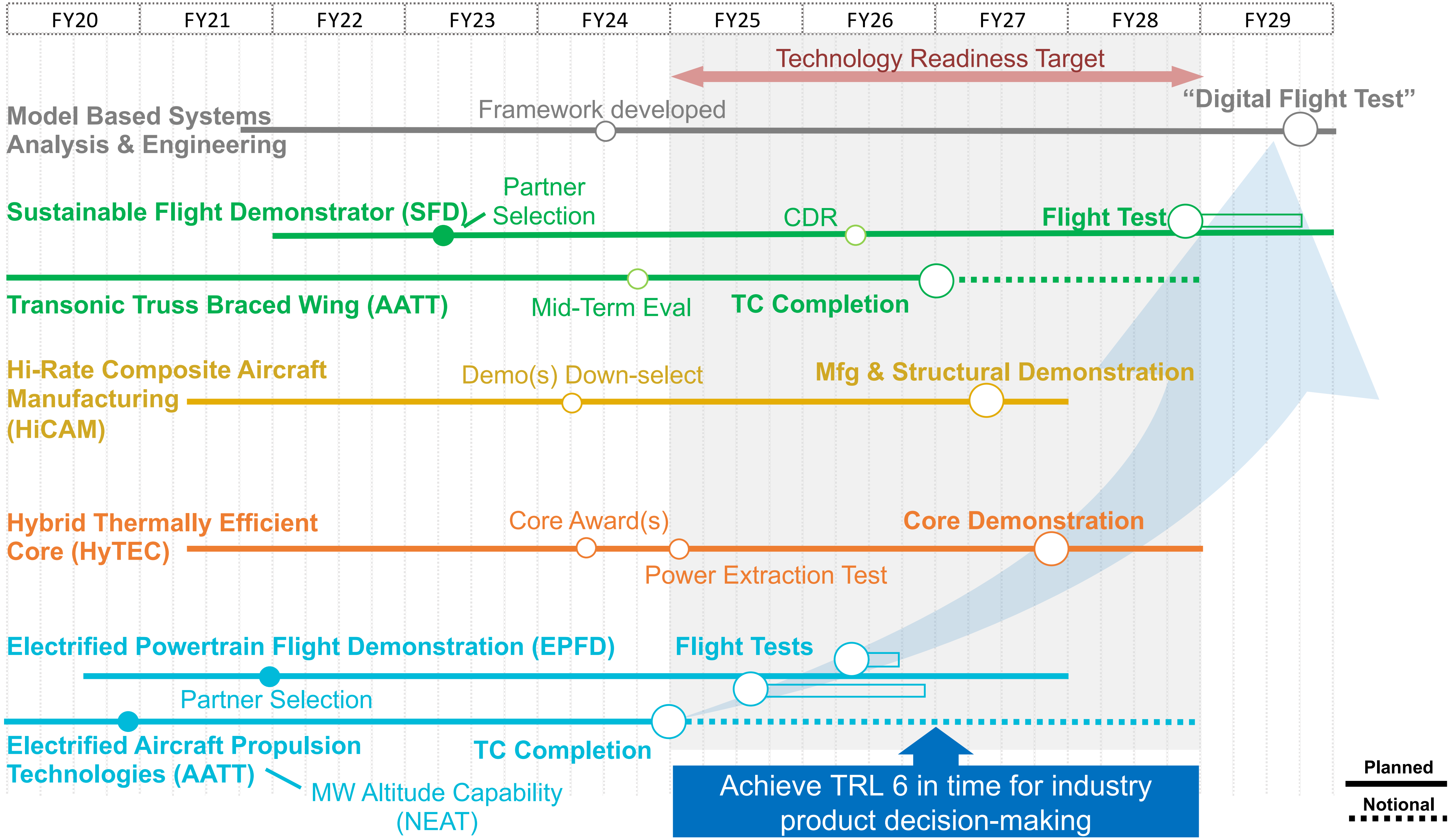


Engine Efficiency
Small Core Gas Turbine
(5-10% fuel burn benefit)

Subsonic Airliners: Integrated Technology Development

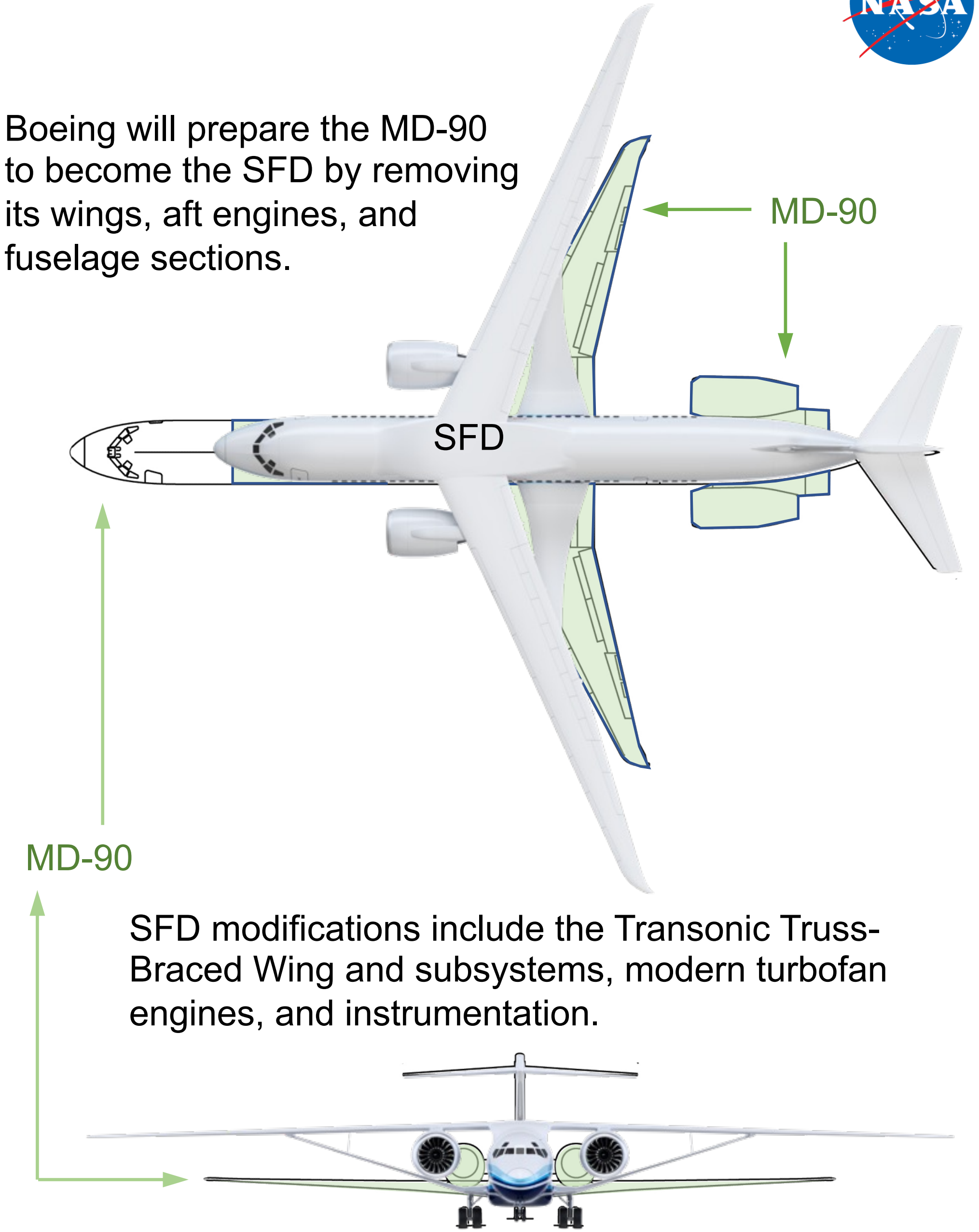




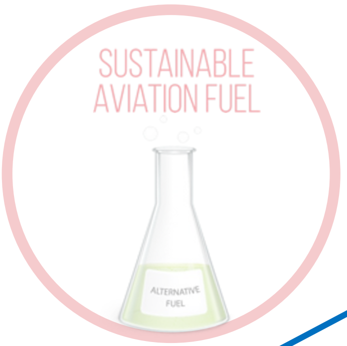


Sustainable Flight Demonstrator Project

- NASA awarded a Funded Space Act Agreement to Boeing in January 2023 to design, build, test and fly an advanced airframe configuration demonstrator aircraft and related technologies to dramatically reduce fuel burn and CO_2 emissions.
  - $425M direct NASA investment + NASA facilities/labor of ~$125M over 7 years
  - $725M funding from Boeing and industry partners
- Boeing's Transonic Truss-Braced Wing configuration utilizes a high aspect ratio, thin, truss-braced wing design to reduce drag and optimize fuel efficiency.



NASA-led SFNP Operations Demonstrations

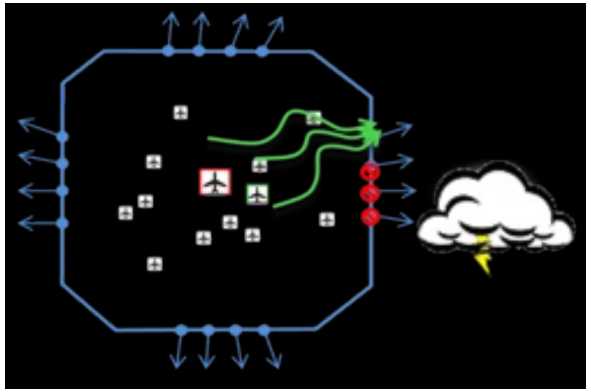


GLOBAL Aviation Goal: 2050 net-zero carbon

- *industry (ATAG)*
- *governments (ICAO)*
- *U.S. Aviation Climate Action Plan.*

Flight Deck Services

Ground Services



Collaborative Digital Departure Re-route (SFNP-Ops-1, FY22-26)

Sustainable Oceanic Airborne Re-Routing (SFNP-Ops-2, FY27)

Irregular Ops Recovery/ Disruption Management (SFNP-Ops-3, FY28)

4D Trajectory Optimization (SFNP-Ops-4, FY30)

SFNP-Ops = Sustainable Flight National Partnerships - Operations

Digital Information Platform (DIP) Sustainability Goals

Deliver reduction in emissions and optimize air operations through digital services

Sustainable Aviation Fuels

Enable the use of 100% sustainable aviation fuels (SAF) and reduce climate impact

Scope

- Support adoption of high-blend ratio sustainable aviation jet fuels

Benefits

- Reduced aviation environmental impact
- Reduced uncertainty for climate impact of aviation-induced cloudiness
- Improved efficiency/emissions with drop-in synthetic and biofuels

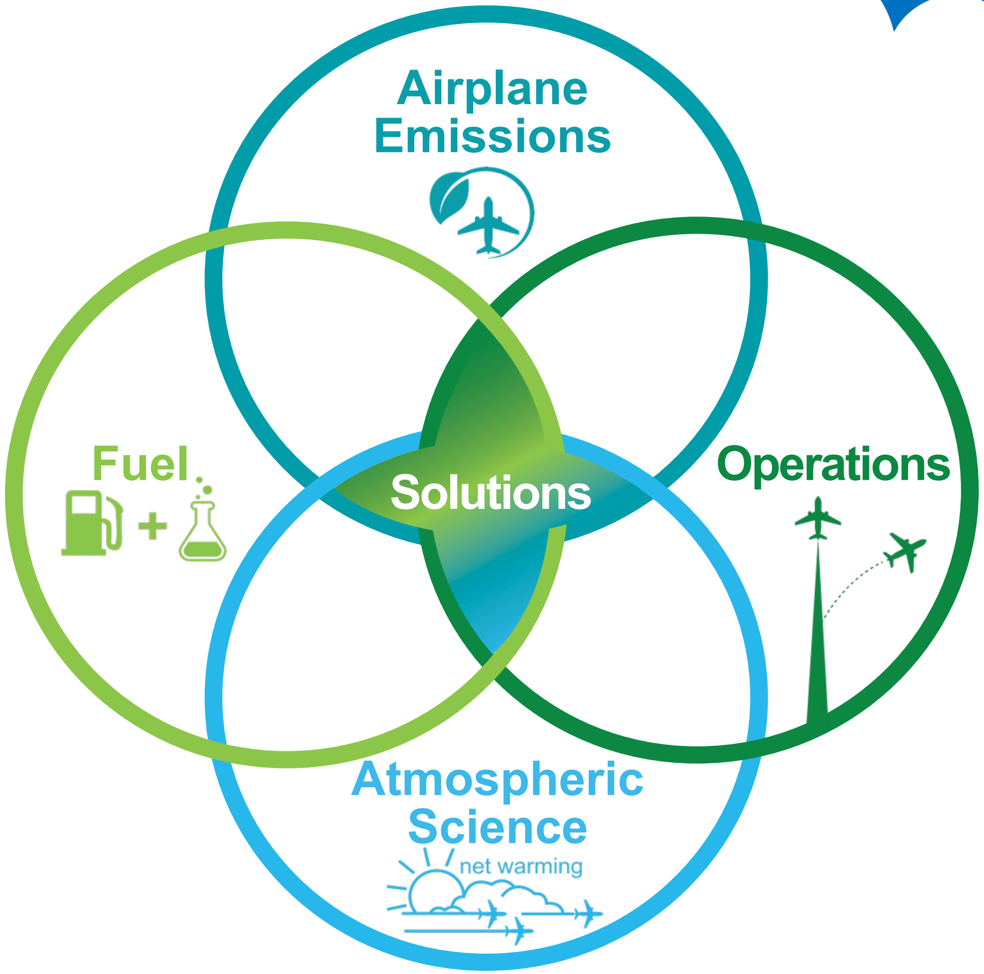
Approach

- Characterize high-blend sustainable aviation jet fuel emissions on ground and in flight

Future SAF & Contrail-related Research Plans in Development

Contrails

- Climate models tell us that aviation-induced cloudiness has a net warming impact comparable to a century of aviation CO2 emissions
- Aviation-induced cloudiness comes from the formation of relatively few but long-lasting contrails caused by:
    1. Airplane Emissions impacted by engine technology and,
    2. Fuel chemical composition, and
    3. Atmospheric conditions – meteorology & chemical reactions
- Focused research in these 3 areas will give us the scientific basis to inform sustainable flight operations decisions to avoid (or not) contrail formation.



Research Areas

Beyond SFNP, Long-Term Transport Technology and Innovation

Generational studies to inform future technology investments

2008-2019 → 2020-2029 → 2030 - 2039 → 2040 - 2050

Subsonic Fixed Wing (2008-2019)

N+2 Studies, ERA for the 2020s Impact (2020-2029)

N+3 Advanced Concept Studies for 2030s Impact (2030 - 2039)

Concept Studies and Technology Development Needed for 2040s Impact (2040 - 2050)

Opportunities to Define Future Aviation Systems and Concepts

- Advanced Concept Studies for 2040+ EIS
- Net-Zero Emissions Concepts
- Promising Technologies and Architectures
- Support Aviation Community with NASA-unique Contributions

Innovations for 2040s and Beyond

IMPLICATIONS for Sustainable Aviation

Time is of the essence – 2050 is only 27 years away and the climate is not waiting
- Given the development cycle of new aircraft, we have one, maybe two shots at new aircraft
- Airplane design and energy infrastructure for aviation must be consistent

Energy-sector transformation is critical including the infrastructure to support it (globally)
- Need clean electric grid and need other sectors to successfully transition
- Need clean hydrogen – this is not inconsistent with a SAF future for aviation
- Need 100% SAF – a lot of it

Energy Efficiency is necessary but insufficient independent of aviation's energy supply
- Cannot "energy efficiency" our way to net-zero
- But less energy required reduces volume required and cost

Climate scientists highlight net-zero carbon (not zero) and reducing non-CO2 impacts as necessary

Fleet/Infrastructure Inertia - If one can create an aircraft using non-drop-in, zero-lifecycle carbon energy, how can the fleet/infrastructure transform – does it take parallel energy supplies/operations for decades?

If lifecycle zero carbon small to regional aircraft (turboprops) become practical reality, can they substantially change the business physics of todays networks? And compete with equivalent technology ground transport?

Related, can larger aircraft with substantially reduced range but cleaner tank to wake emissions substantially change the business physics of todays network?

CONCLUDING REMARKS

- Global aviation faces significant challenges to sustainable growth
  - Halt aviation's contribution to global warming without suppressing flight demand and without out-of-sector offsets, while remaining a viable and valued cornerstone of transportation (safe, clean, quiet, efficient, operable, economical, marketable)
  - Challenges require multiple, often interdependent, solutions across technology, operations, and energy domains
  - No silver bullets

- NASA Aeronautics addressing the challenges of Sustainable Aviation
  - Maturing and demonstrating the most promising solutions for application in the 2030s
  - Exploring innovative solutions for application 2040+

- Celebrate – National Aviation Day is August 19

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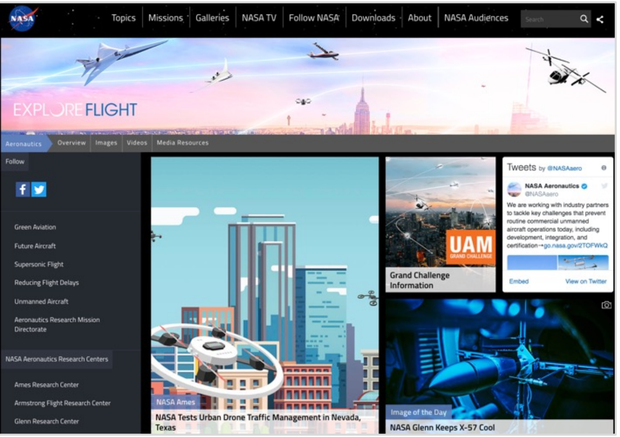

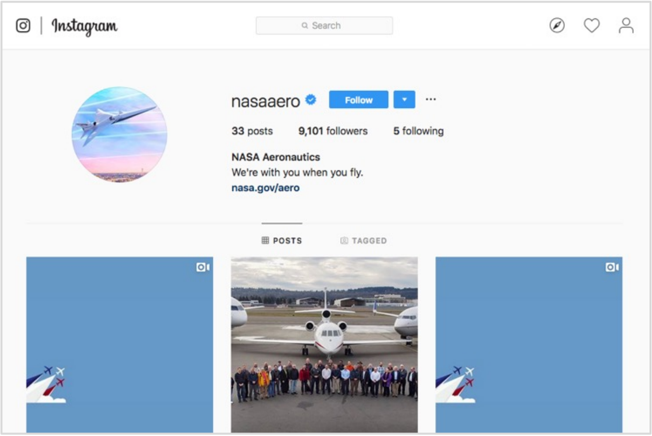

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