***** Extended Abstract *****

Framework for National Airspace System (NAS) Level Sustainability Assessment of New Aircraft

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This paper introduces a framework for investigating the future sustainability benefits of conceptual vehicles. The framework considers the complex interactions between such vehicles and how it can be flown in the National Airspace System. Aggregate benefits for reduction in fuel use and emissions need to consider fleet wide operations, demand distributions, NAS Infrastructure, and differing business models. To extract true system level benefits multi-objective function optimization for operational energy use, acoustics, emissions and NAS Wide efficiency and interoperability incorporating physic-based system-wide flight simulations in the National Airspace system is required. The framework marries traditional vehicle synthesis processes with a NAS Simulation environment to simulate how a new synthesized vehicle will behave in the NAS.

I. Background

NASA is involved in developing key technologies to enable sustainable flight that meet U.S. environmental goals articulated in the U.S. Aviation Climate Action Plan, Figure 1.

The reader will observe that different wedges, representing the emissions improvements of various technologies, within the chart appear distinct and unrelated.

The goals of the climate action plan are to be achieved by a combination of technological advances in the integrated design of new vehicles, new types of propulsion and more efficient fleet operations. The contribution to sustainable aviation at the fleet level is a complex mix of the individual contributions from each source and requires a newframework.

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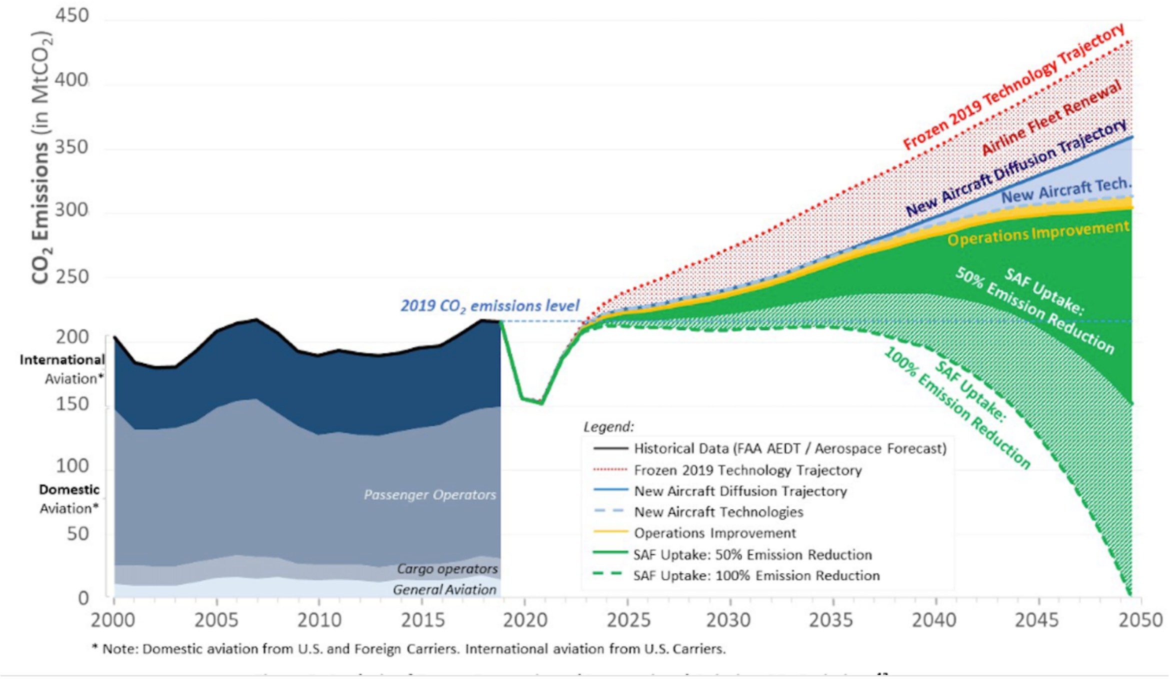


Figure 1: Analysis of Future Domestic and International Aviation CO, Emissions (from U.S. Aviation Climate Action Plan[1])

NASA's Electrified Powertrain Flight Demonstration (EPFD) project focuses on ground and flight tests of electrified aircraft propulsion (EAP) technologies to enable a new generation of electric-powered aircraft. EAP technologies offer innovative solutions to making flight more sustainable – including lighter and more efficient motors, electronics, and materials. NASA seeks to support the introduction of EAP systems into the U.S. commercial fleet.[1]

NASA's Sustainable Flight Demonstration (SFD)] project focuses on developing key airframe technologies, such as improved wing designs, that have a high probability of transition to the next generation of single-aisle seat class airliners, which account for greater than 50% of worldwide aviation emissions. Through SFD, NASA seeks to introduce these novel airframe technologies to the U.S. commercial fleet by conducting ground and flight test demonstrations within the 2030-2040 timeframe and help mature these airframe technologies for entry into the next generation of single-aisle airliners.[2]

Both electrified aircraft propulsion, advanced airframe configurations, and other related technologies have the potential to dramatically reduce aircraft fuel burn and carbon dioxide emissions[2].

II. Vehicle Analysis to Verify Sustainability Goals

NASA employs parametric vehicle modeling and analysis tools s such as General Aircraft Synthesis Program[3] (GASP) and Flight Optimization System4 (FLOPS) to conduct vehicle performance assessments. Both programs provide modeling and integrated multidisciplinary performance analysis for various types of aircraft including electrified aircraft concepts and single aisle airliners. Used during the conceptual and preliminary design phases, GASP and FLOPS facilitate the design and evaluation of advanced aircraft concepts. Within both programs, modules that consider certain parameters such as weight, geometry, aerodynamics, propulsion, and mission performance allow for assessment of the aircraft's performance throughout the design mission.

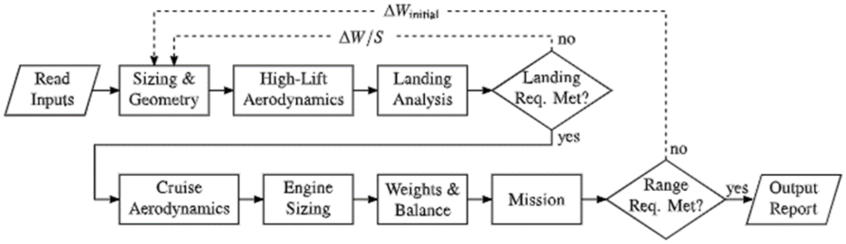


Figure 2: GASP flowchart

These methods are employed to provide independent verification and validation of concepts being pursued to ensure sustainability goals for fuel burn reduction and reduced CO_2 emissions can be realized by vehicles optimized for energy usage and meet acceptable and viable mission profiles. Additionally, the multi-objective function optimization will also consider acoustics.

NASA will leverage the concept models and studies to conduct sensitivity and trade studies of relevant payoff functions to inform future investments in aeronautics research.

III. Extending Vehicle Assessments to encompass System Level Effects

While traditional vehicle analysis techniques are valuable in assessing the performance and benefits of a single vehicle the assessment does not consider the aggregate performance and benefits of such vehicles operating in the national airspace system. Legacy tools idealize trajectories; they typically don't account for the increased fuel burn during turns and use simplified descent profiles that don't consider the complex airspace around airports.

Some benefits or metrics require a system level perspective. Annualized emissions can only be determined at fleet operational levels – ("how the vehicles are actually used" vs "what it was designed for"). Community noise impacts are difficult to assess based solely on ANOPP vehicle analyses and require as-flown trajectories and realistic engine schedules.
NAS Wide Efficiency can only be obtained in a NAS Wide Simulation which consider NAS Infrastructure, rules and constraints, weather, and controller workload.

Multi-objective function optimization for operational energy use, acoustics, emissions and NAS Wide efficiency and interoperability incorporating physic-based system-wide flight simulations in the National Airspace system is required to extract true system level benefits.

IV. Examples of Coupled Benefits

The following are some simplistic examples of the coupled nature of the National Airspace System infrastructure and future sustainability-aspiring aircraft

High Aspect Ratio Wings: We can in theory design a high aspect ratio vehicle that will yield phenomenal fuel savings (on the order of 20%), however that will require very large wingspans that may not be compatible with most airports in the United States. The benefits of introducing such a vehicle into the system would need to be weighed considering the limited operations of between city pairs that can accommodate this vehicle, and/or the cost of adding or modifying airports that can fit the larger span.

Reducing Cruise Mach Speed: It can be argued that tremendous fuel and emission reductions can be obtained just by reducing the speed at which vehicles operate. These vehicles will be expressly designed for optimal performance at these lower speeds. But how will such vehicles interact with other aircraft designed to operate at higher speeds? It can be presumed that this will be the case as older vehicles will still be in operation as the more efficient lower speed vehicles are introduced into fleets. How will operational rules of the Air Traffic Management System, honed over the years with traditional light, medium and heavy tube and wing interactions, accommodate the vehicle speed differences. Is airspace complexity affected? If so, what could be the effect on the throughput of the system?

Electrified Aircraft Propulsion Vehicles: Because of the limited range and payload capabilities of EAP vehicles when compared to existing aircraft, how should such EAP vehicles be introduced into the NAS? When and where should such vehicles be introduced in the NAS? What considerations need to be made with respect to the current and future availability of electric energy generating capabilities.

Again, recognizing EAP's inherently limited range and payload; are there new operating paradigms or business models that will yield more favorable conditions for adoption of EAP vehicles?

Hydrogen Fueled Vehicles: It is likely that intercontinental flights post 2050 will be fueled by hydrogen. The infrastructure required to support hydrogen aircraft at airports and nearby at electrolysis plants to produce hydrogen will fundamentally alter airport operations and the NAS. For example, rather than operating intercontinental flights from many airports within a continent, fewer airports located along coastlines fed by electric aircraft from the continental interior might be more optimal given the energy resources required by green hydrogen production.

V. NAS-level Air Traffic Simulation Platforms

The most efficient flight is an unimpeded wind optimal route with optimal climb and descent. Vehicles are designed to operate efficiently for a certain range, cruise speed and altitude. The vehicle trajectories are degraded due to airport and airspace capacity constraints. The aircraft trajectories are modified in NAS operations to maintain safety while minimizing fuel and operating costs, schedule integrity, delay, and environmental impact. The actual benefits and cost due to the introduction, as well as the level of insertion, can be better estimated in a NAS-wide simulation.

NASA has developed several flexible software-based simulation environments for exploration, development, and evaluation of advanced Air Traffic Management (ATM) concepts[7,9]. They model systemwide airspace operations over the contiguous United States. Airspace models (e.g., Center/sector boundaries, airways, locations of navigation aids and airports) are available from databases. Weather models (winds, temperature, severe weather cells, etc.) are also available. Aircraft trajectories are modeled using spherical-earth equations. The aircraft can be flown along their routes as they climb, cruise, and descend according to their individual aircraft-type performance models. Fig. x1 shows the components of an air traffic simulation environment. The software consists of four components: 1) algorithms, 2) databases, 3) graphical user interface (GUI), and 4) applications. The algorithms use data from the databases and process the information needed by the applications, where each application supports one or many ATM concepts. The applications generate decision support data, which are displayed on the GUI. Real-time aircraft position data and flight plan data are obtained from the FAA's System Wide Information Management (SWIM). SWIM facilitates the data sharing requirements for air traffic operations. Wind, humidity, and temperature data are obtained from the National Oceanic and Atmospheric Administration's weather data feed. The historical data from the static databases and dynamic data feeds are used for parsing the flight plan route and constructing four-dimensional (4D) trajectories for the climb, cruise, and descent phases of flight according to the performance characteristics of the individual aircraft type. These simulations have been used to model air traffic operations at the national and global level, develop innovative new air traffic concepts, and develop real-time traffic advisories used by the FAA and airlines.

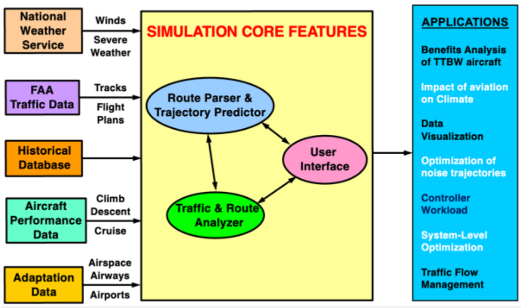


Fig. 3 Components of an air traffic simulation environment.

VI. The Framework

The following is a representation of the new framework wherein we insert new vehicle types into a NAS Simulation environment to obtain systemwide cost benefits.

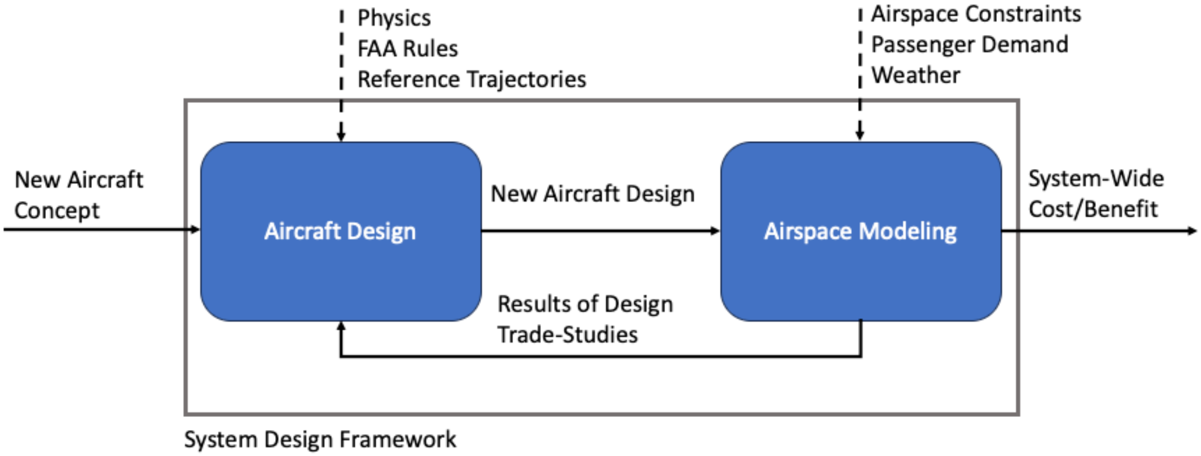


Fig. 4 NAS new-vehicle simulation process.

Challenges to System or NAS level Assesments

VII. Future Studies

Transonic Truss-Braced Wing (TTBW) aircraft

NASA with industrial partners is developing Transonic Truss-Braced Wing (TTBW) aircraft which consists of building an aircraft with extra-long, extra-thin wings that spread over the top of the fuselage. The wing design together with advances in propulsion systems, materials and systems architecture, a single-aisle TTBW airplane may reduce fuel consumption and emissions by as much as 30%. Wing folding is a crucial technology for TTBW aircraft to achieve its desired aerodynamic performance and operational efficiency. The TTBW's long, slender wings provide significant aerodynamic benefits, including reduced drag and improved lift-to-drag ratio. The wing folding technology enables TTBW aircraft to operate efficiently both in the air and on the ground contributing to the development of more sustainable and environmentally friendly air transportation systems. However, these extended wings also pose challenges for ground operations, as they may not fit into standard airport gates or hangars.

As part of NASA Sugar program, Boeing used a 737-type aircraft with a folding wing design mechanism to study the impact of high wingspan aircraft. The unfolded wingspan (approximately 170 feet) will stay within the ICAO Code Letter D wingspan limit and the folded wingspan (approximately 118 feet) will stay within the Code Letter C wingspan limit. The aircraft intends to operate with its wings unfolded on the runway and folded whenever the aircraft is off the runway. The aircraft wings will be compatible with the ICAO Code Letter D runway environment, and Code Letter C taxiways and parking aprons. The aircraft will have design and operational incompatibility on ICAO Code Letter C airport runways as well as with hangars and aprons when the wing is unfolded.

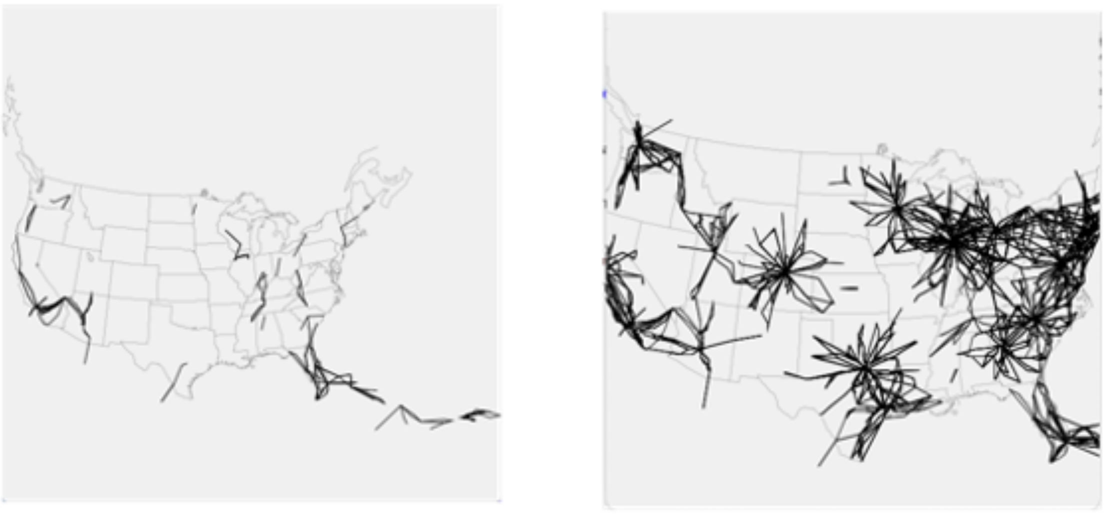
Boeing[8] conducted the study using worldwide airport reference coding distribution by scheduled flights as reported in the Official Airline Guide (OAG) through February 2012.

Boeing identified human acceptance by airport and aviation authorities as a major potential issue with folding wings. It was recognized that the dual status of the aircraft (hybrid Code C/D) will create workload and training challenges to air traffic controllers. Another area of concern is aircraft de-icing procedures. It may be necessary to maintain unfolded-wing configuration after de-icing or provide some sort of on-board anti-icing feature. We plan to conduct several scenarios of increasingly higher fidelity to get a better understanding of the impact of TTBW wing folding on the fleet level performance measured in terms of safety, aggregate fuel usage and emissions and airport and airspace capacity. Some preliminary scenarios:

1. Repeat the Boeing study using traffic and airport data for the U.S using data for 2023. Select a set of Class (III/C) and Class (IV/D) airports considering their role in the NAS.
2. Evaluate the effect of Wing folding TTBW aircraft under different new aircraft insertion levels at different airports.
3. Conduct a detailed surface operations simulation at a Class (III/C) and Class (IV/D) to quantify the impact on taxi times, airport emissions, airport delay and airport capacity.
4. Conduct a low-level human-in-the loop simulation to further understand the controller workload, training and safety issues resulting from dual classification of TTBW aircraft and requirements for de-icing in inclement weather.

Hybrid Electric Aircraft

A NASA study[10] is underway investigating the fuel burn and flight time impacts of hybrid electric aircraft operating in the National Airspace System. The study postulates an operational replacement of existing flights in the NAS with a hybrid vehicle. Future scenarios with hybrid electric flights and the same passenger travel capacity between city pairs are used as a baseline scenario. Aircraft that serviced select flights in the baseline scenario were replaced with hybrid electric aircraft based on the flight’s range and seat capacity. Additional hybrid electric flights were added to future scenarios when necessary to keep the future scenario passenger capacity equal or greater to that of the baseline scenario. Initial results in Figure 4 shows the increased operations resulting from replacement schemes as detailed in the paper. Total fuel burn of the various replacement scenarios will be compared to the baseline case. Operational metrics like total flight time and airport operations will also be determined. Figure 5 shows the added hybrid flights to the NAS in the simulation environment. Figure 6 shows the increased in operations compared to the baseline operations.



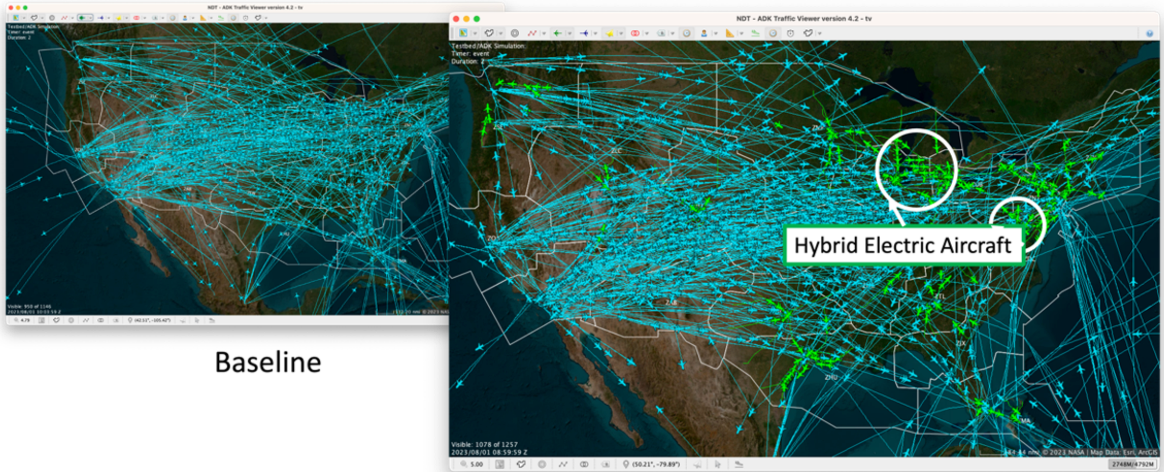
Scenario 1

Scenario 3

Scenario 2

Scenario 4

Fig. 4 Initial Results or Hybrid Vehicle Replacement Scenarios[10]



Baseline

Scenario 2

Fig. 5 Initial Results or Hybrid Vehicle Replacement Vehicles in the NAS[10]

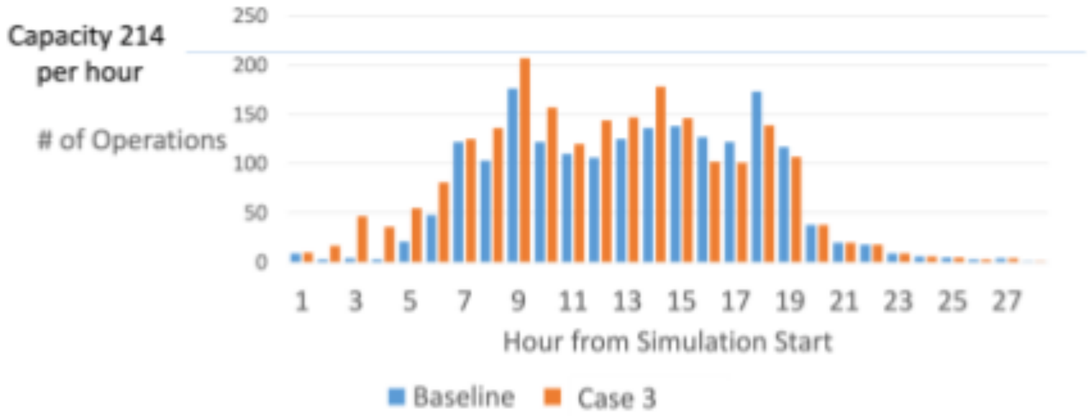


Fig. 6 Initial Results Showing Increased Operations with Additional Hybrid Vehicle w/r to Replacement Scenario 3. [10]

VIII. Conclusions

Envisioning a carbon-neutral aviation future is particularly challenging because of the interdependencies of the systems involved. One of these systems is the NAS which can be simulated using existing tools such as the NAS Digital Twin[9]. Well executed simulation studies are helping to shape sustainable aviation and associated network structure and business operations of the future.

IX. References

1. Federal Aviation Administration. (2021) *United States 2021 Aviation Climate Action Plan* Washington, D.C. GPO https://www.faa.gov/sites/faa.gov/files/2021-11/Aviation_Climate_Action_Plan.pdf
2. NASA Electrified Powertrain Flight Demonstrator Project Webpage, https://www.nasa.gov/directorates/armd/iasp/epfd/
3. NASA Sustainable Flight Demonstrator Project Web Page, https://www.nasa.gov/directorates/armd/iasp/sfd/
4. Melton, J., Go, S., Zilliac, G., Zhang, B., “Greenhouse Gas Emission Estimations for 2016–2020 using the Sherlock Air Traffic Data Warehouse,” NASA/TM-20220007609, Aug., 2022.
5. "GASP - General Aviation Synthesis Program", Vol. 1- Main Program Vol. 2- Geometry, Vol. 3 - Aerodynamics, Vol. 4 - Propulsion, Vol. 5 - Weight and Balance, Vol. 6 - Performance, Vol. 7 - Economics. NASA CR-152303, January 1978.
6. https://software.nasa.gov/software/LAR-18934-1
7. K. Bilimoria and B. Sridhar, FACET: Future ATM Concepts Evaluation Tool, Air Traffic Control Quarterly, Vol. 9, No. 1, 2001, pp. 1-20.
8. Marty K. Bradley, Christopher K. Droney, and Timothy J. Allen, Subsonic Ultra Green Aircraft Research: Phase II – Volume I – Truss Braced Wing Design Exploration, NASA/CR–2015-218704/Volume I, Boeing Research and Technology, Huntington Beach, California, April 2015.
9. Lauderdale, T., Windhorst, R., Coppenbarger, R., Thipphavong, D., and Erzberger, H. “The National Airspace System (NAS) Digital Twin Simulation”, 2024
10. Windhorst, R, Lauderdale, T., Cone, A., Fong, R., Palopo, K. and Phillips, J., “Analysis of Hybrid Electric Aircraft Operations in the National Airspace System”, 2024