NASA/TM-20205006885

Simulation of a Representative Future Trajectory-Based Operations Environment

Terique L. Barney, Kathryn M. Ballard, Bill K. Buck, Matthew C. Underwood, and Ryan C. Chartrand

Langley Research Center, Hampton, Virginia

November 2020

NASA STI Program . . . in Profile

Since its founding, NASA has been dedicated to the advancement of aeronautics and space science. The NASA scientific and technical information (STI) program plays a key part in helping NASA maintain this important role.

The NASA STI program operates under the auspices of the Agency Chief Information Officer. It collects, organizes, provides for archiving, and disseminates NASA's STI. The NASA STI program provides access to the NTRS Registered and its public interface, the NASA Technical Reports Server, thus providing one of the largest collections of aeronautical and space science STI in the world. Results are published in both non-NASA channels and by NASA in the NASA STI Report Series, which includes the following report types:

- TECHNICAL PUBLICATION. Reports of completed research or a major significant phase of research that present the results of NASA Programs and include extensive data or theoretical analysis. Includes compilations of significant scientific and technical data and information deemed to be of continuing reference value. NASA counter-part of peer-reviewed formal professional papers but has less stringent limitations on manuscript length and extent of graphic presentations.

- TECHNICAL MEMORANDUM. Scientific and technical findings that are preliminary or of specialized interest, e.g., quick release reports, working papers, and bibliographies that contain minimal annotation. Does not contain extensive analysis.

- CONTRACTOR REPORT. Scientific and technical findings by NASA-sponsored contractors and grantees.

- CONFERENCE PUBLICATION. Collected papers from scientific and technical conferences, symposia, seminars, or other meetings sponsored or co-sponsored by NASA.

- SPECIAL PUBLICATION. Scientific, technical, or historical information from NASA programs, projects, and missions, often concerned with subjects having substantial public interest.

- TECHNICAL TRANSLATION. English-language translations of foreign scientific and technical material pertinent to NASA's mission.

Specialized services also include organizing and publishing research results, distributing specialized research announcements and feeds, providing information desk and personal search support, and enabling data exchange services.

For more information about the NASA STI program, see the following:

- Access the NASA STI program home page at http://www.sti.nasa.gov

- E-mail your question to help@sti.nasa.gov

- Phone the NASA STI Information Desk at 757-864-9658

- Write to:
  NASA STI Information Desk
  Mail Stop 148
  NASA Langley Research Center
  Hampton, VA 23681-2199

NASA/TM-20205006885

Simulation of a Representative Future Trajectory-Based Operations Environment

Terique L. Barney, Kathryn M. Ballard, Bill K. Buck, Matthew C. Underwood, and Ryan C. Chartrand

Langley Research Center, Hampton, Virginia

National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

November 2020

Acknowledgments

This work was conducted under the NASA Airspace Operations and Safety Program, Air Traffic Management – Exploration (ATM-X) Project, Increasing Diverse Operations (IDO) Subproject. This activity would not have been completed without the support of the following team members, support personnel, and individuals:

NASA Crew Systems and Aviation Operations Branch: Brian Baxley, Dr. Elaine Blount, Dr. Jennifer Kibler, Neil O'Connor, Ron Maddox

NASA ATM-X IDO: Dr. Bryan Barmore, James Chartres, Rosa Oseguera-Lohr, Dr. Sara Wilson

NASA Internal Contracts:

NIA: Bill Cotton, Thomas Graff, Clay Hubbs, Ken Jones, David Pyke, Joseph Burris, Dr. David Edwards

LITES II: Beau Branch, Chad Chapman, Bill Coppedge, Jim Davis, Mike Day, Mike Havlin, Richard Jessop, Dan Johnson, Dr. David Karr, Troy Landers, Joe Mason, Doug Mielke, Jim Sturdy, David West

TEAMS 3: Jake Barry, Tom Britton, David Wood, Greg Wrenn

NASA Subject Matter Experts: Dr. Husni Idris, Dr. Paul Lee, David Wing

Available from:

NASA STI Program / Mail Stop 148
NASA Langley Research Center
Hampton, VA 23681-2199
Fax: 757-864-6500

This report is also available in electronic form at http://www.sti.nasa.gov/ and http://ntrs.nasa.gov/

Table of Contents

List of Figures

List of Tables

List of Appendix Tables and Figures

List of Acronyms

ADS-B	Automatic Dependent Surveillance – Broadcast
ANSP	Air Navigation Service Provider
AOP	Autonomous Operations Planner
ARTCC	Air Route Traffic Control Center
ASTOR	Aircraft Simulations for Traffic Operations Research
ATC	Air Traffic Control
ATM	Air Traffic Management
ATOS	Air Traffic Operations Simulation
CPDLC	Controller-Pilot Data Link Communications
FAA	Federal Aviation Administration
FMS	Flight Management System
HITL	Human-In-The-Loop
HLA	High Level Architecture
IDO	Increasing Diverse Operations
LaRC	Langley Research Center
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
RAP	Rapid Refresh Product
RPFMS	Research Prototype Flight Management System
STAR	Standard Terminal Arrival Route
SUA	Special Use Airspace
SWIM	System Wide Information Management
TAP	Traffic Aware Planner
TASAR	Traffic Aware Strategic Aircrew Requests
TBO	Trajectory-Based Operations
TMX	Traffic Manager
TOA	Time of Arrival
UTC	Coordinated Universal Time
ZOB	Cleveland Air Route Traffic Control Center

Abstract

Trajectory-Based Operations in the National Airspace System is a key aspect of advanced air traffic management research. Trajectory-Based Operations focuses on modernizing the current operating paradigm to increase efficiency, predictability, resilience, and flexibility while migrating toward greater operational autonomy across the airspace. Research conducted at the National Aeronautics and Space Administration supports the transition from current airspace operations to Trajectory-Based Operations targeting a 2035-2045 implementation timeframe. Simulation scenarios that demonstrate a representative Trajectory-Based Operations environment in that timeframe, and enable the evaluation of advanced airborne tools such as strategic airborne trajectory management services, are necessary to support this research effort. This report describes characteristics and assumptions made about the future operating environment that were applied to a scenario development methodology to study a representative 2040 Trajectory-Based Operations environment in a simulation use case. This report also includes descriptions of the study design and analysis approach, discussion of the simulation results, and application of these scenarios to future research activities.

1. Introduction

The National Aeronautics and Space Administration (NASA) is conducting research focused on the exploration of a future service-based airspace system enabling increasingly diverse operations in dense, controlled airspace [1]. New entrants such as supersonic flights over land, space launch and re-entry vehicles, high-altitude long endurance aircraft, unmanned aircraft systems, and urban air mobility systems are expected to introduce the greatest diversity as their demand for entering controlled airspace increases. However, it is just as important to ensure that the future airspace system accommodates traditional users such as commercial passenger and cargo airlines, business jets, and general aviation, while maintaining or improving current-day levels of safety and security.

The use of a service-oriented paradigm to provide equitable, safe, and secure access to the airspace for all users, vehicles, and missions has been identified as a goal of the new airspace system. The philosophical tenets [1] of this new airspace system include:

1) Scalability for increased demand across users and missions;
2) Flexibility wherever possible and structure only where necessary;
3) Collaboration through integrated information exchange;
4) Resilience to uncertainty, degradation, and disruptions through local empowerment of decision making; and
5) Increased availability and use of user and third party services.

Current research activities at the NASA Langley Research Center (LaRC) are defining airspace services for the 2035-2045 timeframe that improve efficiency and predictability for traditional users, and that prepare the system for increased diversity from new entrants. This paradigm shift is enabled by leveraging existing or soon-to-come technologies built on the principles of information sharing, traffic flow management, and time-based scheduling. In the 2035-2045 timeframe, it is envisioned that these services will be fully integrated with each other and used for gate-to-gate operations for traditional airspace users.

To understand this future service-based airspace system, simulations representative of the operational environment must occur. This report describes characteristics and assumptions of a 2035-2045 Trajectory-Based Operations (TBO) operational environment, discusses a methodology and process for creating simulation scenarios that represent this operational environment, explores a simulation use case within which operations in these scenarios are examined, and presents results from analyses that characterize the simulated TBO environment.

2. TBO Characteristics

The service-based TBO environment for the target timeframe is expected to exhibit a number of unique characteristics not inherent to the airspace environment of today. Information related to these characteristics, the context of their applicability, and rationale behind their existence and implementation, was collected and discussed with air traffic management subject matter experts throughout a series of research forums. Key TBO characteristics and attributes with a high likelihood of relevance to airspace environments in the 2035-2045 timeframe were selected for representation within scenarios.

Information such as aircraft state and intent data, and airspace system-level constraints, will be widely disseminated across the system to multiple stakeholders. Digital Data Communication, or “Data Comm” [2, 3], between airspace users and ATM managers will be routinely used to request complex trajectory modifications and to receive clearances during all phases of flight. Aircraft are expected to fly closed-loop, four-dimensional (4-D) trajectories for the duration of their flight. These trajectories will include consideration of time of arrival (TOA) constraints [4, 5, 6], lateral route constraints, altitude constraints, and speed constraints [7].

The 2035-2045 TBO environment will also allow for services that increase airspace flexibility [8, 9, 10, 11, 12] where desired (e.g., en route flights in Class A, center airspace where user-preferred trajectory negotiations are expected to be most frequent and effective), and structure only where required (e.g., terminal airspace where flow-management constraints are expected to be most prevalent). The implementation of technologies across the National Airspace System (NAS) as part of the Federal Aviation Administration (FAA)’s NextGen program [13] will increase the use of time-based flow management [14] and improve upon how existing system capacity is utilized. These technologies, which serve as the foundation of this future airspace system, are anticipated to increase the predictability of the NAS, as well as increase system and user efficiency in the future TBO environment.

3. Simulation Use Case: A Representative 2040 TBO Environment

The investigation of a 2040 service-based TBO airspace system requires a simulation of a representative TBO environment containing anticipated characteristics for the target timeframe. To support the investigation, simulation scenarios containing the TBO characteristics described in Section 2 were methodically developed. In an example application of the methodology, referred to as the simulation use case in this paper, a set of variables were applied to a particular portion of traffic operations executed in the NAS in an initial exploratory study. The following subsections describe the operational environment for the simulation scenarios applied to the use case, including the selected airspace of interest for the simulation, the accompanying airspace traffic, and environmental factors considered. Simulation capabilities used in the simulation use case, as well as an overview of the process for developing simulation scenarios, are also presented.

3.1 Airspace of Interest

The center airspace structure [15] of today is expected to exist in the 2040 TBO environment, albeit with an increase to air traffic densities to align with projections for annual traffic increases [16]. Class A airspace is also expected to have the most frequent en route trajectory negotiation activities in the target TBO environment. As such, it is the focus of this activity and must be included in the airspace of interest.

Cleveland Air Route Traffic Control Center (ARTCC), referred to as ZOB, Class A airspace was chosen as the airspace of interest for this activity. Figure 1 presents the airspace of ZOB and the surrounding control centers and high altitude airways. The ZOB airspace structure includes several high-density parallel routes and multi-axis merging geometries that enable a large volume of en route traffic. Throughout the course of a nominal day, traffic flows transition between predominantly east to west in the morning, mixed direction during the midday period, and west to east during the evening and overnight. ZOB is surrounded by busy traffic regions, including New York, Indianapolis, and Chicago airspaces, each feeding a large amount of traffic into ZOB. Focus on ZOB Class A airspace avoids the coordination and traffic flow management complexities of terminal traffic that occurs at altitudes below 18,000 feet, and enables greater control over experimental additions. These characteristics make ZOB a suitable candidate for this simulation use case.

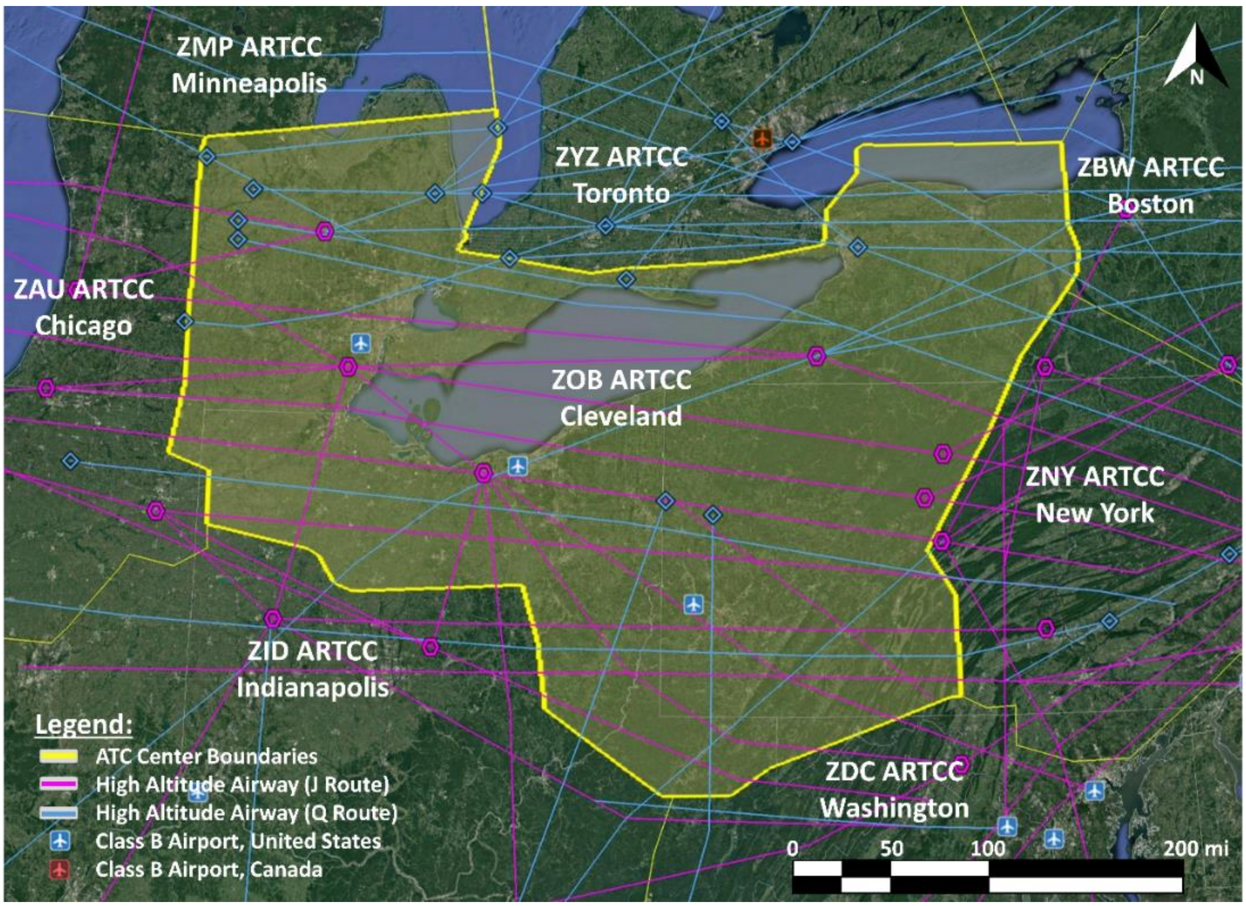

Figure 1: Airspace of Interest for 2040 TBO Simulation – Cleveland ARTCC

3.2 Airspace Traffic

Airspace traffic data were collected for all aircraft traversing ZOB on May 23, 2018, and May 24, 2018, from the FAA's System Wide Information Management (SWIM) system. This enabled real-world routes to be depicted within the simulation. These dates were selected because the two days represented minimal convective weather impact days in the local region[1]. The traffic data were separated into two major categories for data analyses: traffic of interest and background traffic. A portion of aircraft in the traffic of interest category were equipped with an airborne trajectory management capability that provided user-preferred routing (or "free-route") that made efficient use of airspace flexibility, while the rest remained on their original as-flown (or "fixed-route") routing.

3.2.1 Traffic of Interest vs. Background Traffic

The traffic of interest group includes only subsonic jet transport aircraft that fly above 18,000 feet during the entire ZOB portion of en route flight, initialize at least 10 minutes outside of ZOB airspace, and fly for at least 30 minutes within ZOB airspace. Traffic of interest primarily consists of commercial airliners, business jets, and cargo aircraft. Aircraft in this group are equipped with the advanced airborne trajectory management technology, and are the primary focus during post analysis activities.

Background traffic consists of aircraft that did not meet all of the criteria for traffic of interest. This group commonly included turboprop aircraft, aircraft departing and arriving within ZOB, low altitude aircraft, and aircraft that traverse small sections along the edges of the ZOB airspace. Inclusion of background traffic in the simulation environment enabled proper representation of original airspace densities.

3.2.2 Free Route vs. Fixed Route Aircraft

The target 2040 TBO airspace is assumed to consist of a mixture of aircraft both equipped and non-equipped with advanced airborne trajectory management technology. Therefore, aircraft in the simulation are split between approximately 60% equipped with the airborne trajectory management service and 40% non-equipped. Conventional Flight Management System (FMS) capabilities on equipped aircraft are modified in the simulation to include the airborne trajectory management service, which provides fuel-optimized route modifications (i.e., "free routes").

The 2040 TBO request and review process for making trajectory modifications is expected to be more streamlined than current practices; approval of route modification requests by the Air Navigations Service Provider (ANSP) is expected to occur with minimal latency, allowing those aircraft to make use of flexibility in the airspace to lessen operating costs. Therefore, modified trajectories proposed from equipped aircraft in the simulation are approved with little delay. The incorporation of Controller-Pilot Data Link Communications (CPDLC) messages enables rapid execution of optimized route modifications in the simulation [2, 3].

Fixed route aircraft maintain their original route flown from the recorded baseline traffic data and are not permitted to implement any route modifications – regardless of whether the aircraft is in the Traffic of Interest or Background Traffic group.

---

[1] Subsequent TBO scenarios may consider incorporating various levels of convective weather activity to determine its impact on en route air traffic operations, and/or to investigate the ability of the service-based technologies evaluated in the simulation to operate in an environment with dynamic convective weather.

3.3 Environmental Factors

To represent the local airspace environment, several data sources were identified to be included in the scenarios to provide an additional level of realism. The aircraft chosen for the simulation commonly interact with the weather (winds aloft, temperatures aloft, and convective activity), and Special Use Airspace (SUA). The following sections describe the use of real-world winds and temperature data gathered from the National Oceanic & Atmospheric Administration (NOAA) and real-world special use airspaces gathered from the FAA. Note that while the capability to include convective weather in this simulation use case exists (discussed in [17]), the traffic days used in the initial simulation use case were chosen in part because they did not feature any convective weather. This was done in order to ensure the system would be evaluated on a nominal day unaffected by convective weather-induced, non-normal operations.

3.3.1 Winds and Temperature Data

To provide an increased level of realism and to match the recorded as-flown conditions of aircraft for the selected traffic days of interest, archived recordings of winds and temperature aloft were processed and used within the simulation environment. The selected source of the wind and temperature data was the NOAA Rapid Refresh Product (RAP) [18]. The data within the RAP model are updated hourly, and the RAP model contains information for North America on a uniform 40-kilometer grid. The selected sub-products in the RAP are the north-south winds, east-west winds, and air temperature – with an altitude component in terms of pressure levels.

Wind and temperature data from NOAA are actively archived at NASA LaRC for air traffic operations research [19]. The RAP data are processed and stored within individual data files for a specified time and date in a format that is compatible with NASA Langley simulation environments. These files combine the horizontal wind components and temperature data into a 3-D reference data set used within the simulation scenarios.

3.3.2 Special Use Airspace

SUAs are designated portions of the NAS that are defined because of a specific need or use, either for select aircraft use or for a warning/alert area [15, 20, 21]. The shape of SUA is a defined set of three dimensions defining an area above the earth's surface that may occupy varying vertical ranges. Each SUA also has a stated duration that defines if it is active (in effect) or inactive. SUAs may be designated as prohibited areas, restricted areas, warning areas, military operations areas, alert areas, controlled firing areas, or national security areas. SUAs that are included in the developed TBO scenarios for the planned airspace of interest are from the restricted category.

The SUA data in the use case scenarios are created by merging two separate data sources together into a data format compatible with the simulation environment. The first source of information, the FAA Coded Instrument Flight Procedures Navigation Database, provides the three-dimensional geometries of SUA. The second component of the information required is the activation/ deactivation schedule of the SUA, and it is provided by the FAA in a digital format. Both data sources are actively archived at NASA LaRC for air traffic operations research.

3.4 Simulation Capabilities

The development of air traffic scenarios for a simulated 2040 TBO environment makes use of, and builds upon, several simulation capabilities at NASA LaRC. The following sections describe these enabling and supporting capabilities for the simulation of a 2040 TBO environment.

3.4.1 *Air Traffic Operations Simulation*

The NASA Langley Air Traffic Operations Simulation (ATOS) software provides an environment for exploring future airspace operations, including airspace modeling; realistic communication, navigation, and surveillance capabilities; prototype flight deck technologies; and advanced crew display interfaces. It serves as a platform for the development of advanced flight guidance, decision support systems, and operational procedures within research applications. ATOS is capable of simulating hundreds of aircraft using multiple simulation platforms and various aircraft performance models. ATOS has been developed and extended for many years at NASA Langley to support experiments of multiple batch and piloted simulation studies [22, 23].

ATOS has the ability to interoperate with other simulations to enable medium-fidelity simulation of airspace operations. ATOS uses a High Level Architecture (HLA) federation of networked medium-fidelity workstation-based aircraft, a simulation manager, air traffic generators, and network gateways to simulate a representative airspace of interest. Figure 2 presents a conceptual simulation architecture diagram of ATOS.

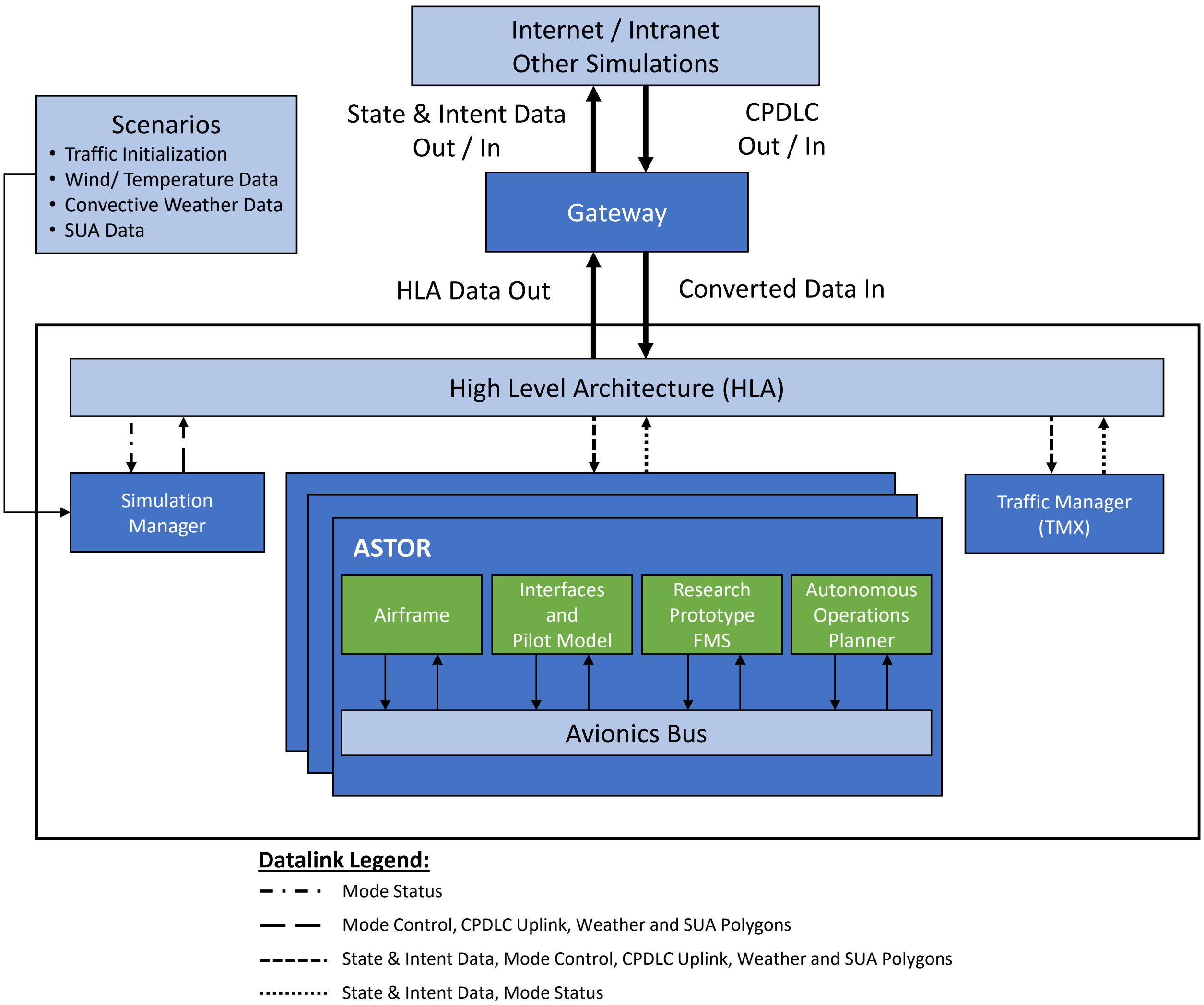

Figure 2: Conceptual ATOS Architecture Diagram

The HLA allows simulated aircraft from various platforms (described in Section 3.4.2 and Section 3.4.3) to operate in and communicate with one another in the same airspace environment. This capability enables a TBO airspace environment to be simulated with significantly higher traffic density than is typically observed in modern-day traffic management operations. The ATOS capability of hosting ASTOR aircraft equipped with an advanced airborne trajectory management technology, the Autonomous Operations Planner (AOP), discussed in Section 3.4.4, serves as the strategic trajectory management service that creates the optimized “free routes” discussed in Section 3.3.2, making AOP critical for the simulation use case.

3.4.2 Traffic Manager

The Traffic Manager (TMX) simulation capability is a low-to-medium-fidelity simulation that has been jointly developed by the Royal Netherlands Aerospace Centre, formerly known as the National Aerospace Laboratory of the Netherlands, and NASA LaRC [24, 25, 26]. It is capable of simulating hundreds to thousands of aircraft in a variety of operational environments. TMX can be used for several different simulation roles, including: a rapid prototype development environment, a scenario generation tool, a traffic generator, a fast time simulation platform, and a real-time simulation platform that integrates with external simulations. TMX has many features that represent operational capabilities, which include a pilot model, air traffic controller (ATC) model, Automatic Dependent Surveillance – Broadcast (ADS-B) model, CPDLC model, 4-D wind model, and advanced airborne avionics. TMX has been used in multiple simulation studies for air traffic operations research and improvements for airborne merging and spacing concepts [26, 27].

TMX was selected to support the scenarios for a TBO simulation environment to provide realistic high-density background traffic that minimized the overall simulation network and hardware infrastructure. TMX is able to simulate a large amount of aircraft on a single computer/network due to its comparatively lower level of fidelity. All TMX aircraft communicate with ATOS through a single connection in an HLA network. In contrast, each ASTOR instance needs its own individual HLA connection within an executed scenario. TMX is a valuable addition to the simulation use case given the need to simulate thousands of aircraft per scenario, the limited number of simulation connections that the current ATOS HLA architecture can support, and the TMX ability to simulate a large number of aircraft within a single network connection.

3.4.3 Airspace Simulations for Traffic Operations Research

The NASA Langley Airspace Simulations for Traffic Operations Research (ASTOR) is a medium-to-high-fidelity, networked, and interactive desktop simulation of commercial transport aircraft and its flight deck systems [28, 29]. An ASTOR in simulation consists of multiple components, including a customizable FMS, environment sensors, data communication emulation, surveillance emulation, cockpit display and control panels, a customizable pilot model and a high-fidelity aircraft performance model. The aircraft performance model used within an ASTOR is based on the NASA Langley Standard Real-time Simulation in C++, a high-fidelity vehicle simulation [30]. Reference [17] further discusses the capabilities of ASTOR and its use in this simulation use case. Further information regarding ASTOR and supported applications is also provided in references [22, 23, 28, 31, 32].

In the simulation use case described in this document, ASTORs were used to represent portions of all airspace traffic types, including traffic of interest and background traffic. Additionally, ASTORs are also the only simulation type capable of representing free-route aircraft, because ASTOR interfaces with AOP. Therefore, the capabilities of ASTOR aircraft are critical to the implementation and execution of optimized trajectories in the simulation use case.

Each ASTOR performance model possesses a unique set of simulation specifications that are associated with a real-world aircraft type. Each aircraft in the scenarios was represented by the model whose performance attributes most closely matched its associated aircraft type in the simulation use case. Example specifications for aircraft types represented by ASTOR performance models in the simulation use case are provided in Table 1.

Table 1: Typical Specifications for Aircraft Types Represented by ASTOR Performance Models

ASTOR Model	Aircraft Type	Service Ceiling (ft.)	Maximum Takeoff Weight (lbs.)	Cruise Speed (Mach Number)
NASA_HU25	Business/Regional Jet	42,000	32,000	0.64
NB137_2E22	Narrow-body Short Range	37,000	137,000	0.76
NB172_2E27	Narrow-body Medium Range	41,000	172,500	0.78
NB250_2E40	Narrow-body Long Range	41,000	250,000	0.78
WB315_2E48	Wide-body Medium Range	41,000	315,000	0.78
WB535_2E77	Wide-body Long Range	43,100	535,000	0.79

3.4.4 Autonomous Operations Planner

The AOP technology is a NASA-developed flight deck-based prototype software tool that provides the trajectory management functions of conflict detection, resolution, and prevention; constraint compliance; and coordination with other vehicles [33]. The AOP software has been refined and matured through multiple batch experiments and pilot simulations since the early 2000s [34, 35, 36, 37, 38, 39]. The evolution of AOP has also contributed to multiple research concepts developed at NASA, including the Traffic Aware Strategic Aircrew Requests, or TASAR, concept and its technology prototype, the Traffic Aware Planner (TAP) [9]**.**

The current implementation of AOP, AOP Version 2 (AOPv.2), merges the conflict detection and resolution capabilities of AOP with the trajectory optimization capabilities of TAP. The merger creates a single airborne tool that can be applied to research and development of advanced trajectory management concepts that have been years in the making. There are two main operating modes of AOPv.2: conflict avoidance and optimization.

- Conflict Avoidance: This mode is entered if the active route is predicted to have an airspace conflict (e.g., traffic, weather, Special Use Airspace). The AOPv.2 technology provides the flight crew with trajectory modification guidance to resolve the conflict in the most efficient manner (e.g., least fuel or least time).
- Optimization: This mode is entered if the active route is predicted to be de-conflicted. The AOPv.2 technology provides the flight crew with trajectory modification advisories to optimize the current flight path (e.g., minimize fuel burn, minimize flight time, and minimize trip cost) while respecting known airspace constraints and avoiding conflicts with known airspace hazards. There are three types of trajectory modification solutions: Lateral, Vertical, and Combination Lateral plus Vertical (known as Combo) solutions.

AOPv.2 makes use of assumed TBO capabilities, including:

- Data Comm avionics and Full En Route Data Comm services [10];

- Time Based Flow Management automation and FMS Required Time of Arrival meeting capabilities [11]; and
- Trajectory Flow Management System automation: Airborne Rerouting, Trajectory Option Set, and Route Amendment Dialogue functionality [12].

3.5 Scenario Development Methodology Overview

Representative simulation scenarios need to be developed that provide a realistic environment to evaluate service-based airspace operational concepts and technologies for the envisioned 2040 TBO timeframe. The planned outcome of the scenario development process is the creation of 10 baseline TBO scenarios (two days with five time-periods each) that could be used in current and future ATM simulations. Following the methodology described in [17] and highlighted in this section, the scenarios were developed using a sequence of managed stages, automated scripts, and an iterative data collection process. The scenarios feature real-world traffic archived at NASA Ames Research Center as a starting point, real-world wind and temperature data gathered from NOAA and archived at NASA LaRC, and real-world SUA data gathered from the FAA and archived at NASA LaRC. All data are pre-processed to work with existing ATOS or TMX simulation capabilities.

The development of these scenarios had several requirements to be met or exceeded, to serve the needs of the larger program and potential follow-on activities. The four core requirements for the scenario development process are:

1) Use real-world aircraft route data (SWIM) as a basis for traffic data
2) Use 4-D winds and SUA for increased realism
3) Mixed equipage for services: 60% advanced-services equipped aircraft, 40% baseline equipage
4) High density airspace should emulate 2040 traffic projections

These requirements dictated the process by which the archived SWIM data were adjusted to fit into a form compatible with the ATOS environment. Additionally, these requirements were checked at the end of each stage of scenario processing before proceeding forward. The simulation configuration and use case scenario development processes are described in the following sections.

3.5.1 Configuration to Enable the Simulation Use Case

Adjustments were required to make the final scenario file for the time-periods of interest compatible with the ATOS environment. To achieve the TBO characteristics presented in Section 2 (provided below as the first-level bullets), design the airspace according to the parameters in Sections 3.1 through 3.3, and make use of the simulation capabilities in Section 3.4, the following simulation configuration options were enabled. Further details on the simulation configuration parameters are provided in [17].

- Wide dissemination and use of system-level constraints
  - Real-world wind data, properly formatted for use in ATOS, is used in the simulation.
  - Real-world convective weather and Significant Meteorological Information data, properly formatted for use in ATOS, is enabled in the simulation.
  - Real-world SUA data, properly formatted for use in ATOS, is used in the simulation.
  - Altitude and speed constraints during the arrival phase of flight are present on aircraft routes.
- Wide dissemination and use of aircraft state and intent
  - ATOS ADS-B Out model is used to broadcast aircraft state data.
  - ATOS ADS-B In model is used to receive aircraft state data from nearby traffic.

    - ATOS Automatic Dependent Surveillance – Contract Extended Projected Profile model is used to broadcast aircraft trajectory intent data.
- Routine use of Data Comm to request complex trajectory modifications and to receive clearances
    - ATOS Data Comm model is used to send route change clearances to aircraft.
- Aircraft always fly on 4-D trajectories
    - ASTOR's Research Prototype FMS (RPFMS) computes 4-D trajectories for all ASTOR aircraft.
    - ASTOR guidance, auto-flight, and auto-throttle systems are used to execute 4-D trajectories.
- Flexibility where desired, structure where required
    - The level of structure in the airspace is reduced by removing altitude constraints above FL180 to increase potential flexibility.
    - For equipped aircraft, use an early version of AOPv.2 as a surrogate technology to provide flexible "free routes" that optimizes the route for fuel savings.
    - Make use of ATOS/RPFMS capabilities to model Standard Terminal Arrival Routes (STAR) and approaches to known runways.

3.5.2 Simulation Use Case Scenario Development Process Overview

Once the simulation environment is configured properly, scenarios are required to exercise the simulation capabilities and provide data for analyses. The complexity of the scenarios required for this activity necessitated the separation of the scenario generation process into multiple, managed stages. Each stage provided a meaningful milestone in the process of separating flights into the groups provided in Section 3.2, providing corrective measures to the aircraft's state and route, and selecting traffic for post-hoc data analyses. The four stages are presented below in Figure 3, and more detail is provided in [17].

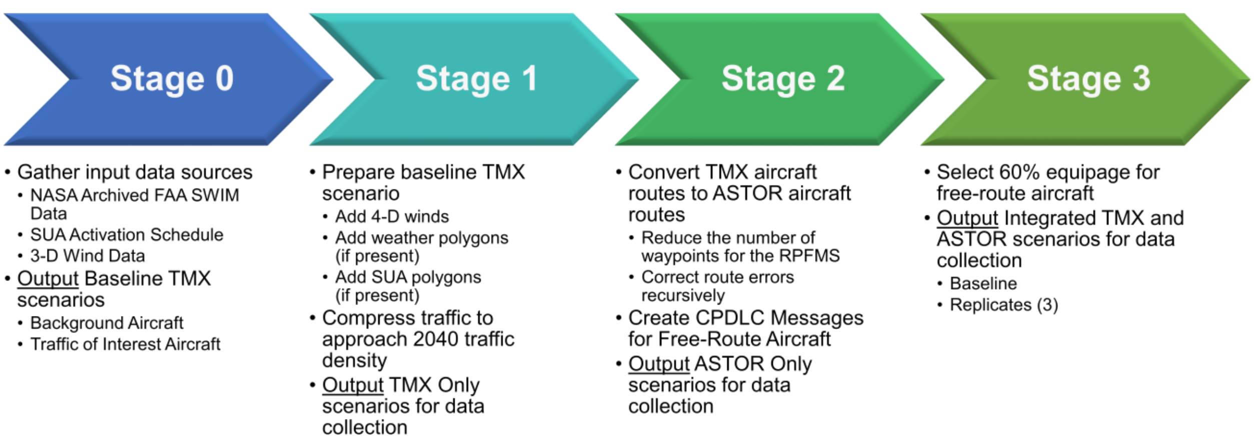

Figure 3: 2040 TBO Environment Simulation Scenario Development Staging Process

The current approach to developing representative 2040 TBO environment simulation scenarios includes a four-stage process. During the first stage (Stage 0), SWIM data containing routes as flown by aircraft in the NAS during the specified days/times of interest are processed and converted into TMX scenario files compatible with a basic TMX simulation. Wind, temperature, and SUA data are also prepared for the day/time of interest in Stage 0, and added to the TMX scenarios.

During Stage 1 of the scenario development process, aircraft are identified and separated into Traffic of Interest and Background Traffic based on research criteria. Air traffic density is also increased during this stage to approximate traffic in the 2040 timeframe. Stage 1 results in a data collection activity using TMX and the data are reviewed to ensure that all aircraft in the scenario fly their respective routes properly.

The next stage (Stage 2) of the scenario development process converts some aircraft from the Stage 1 TMX scenarios to ASTOR aircraft, which enables those aircraft to integrate with the early version of AOPv.2. Throughout the conversion from TMX aircraft to ASTOR aircraft, corrective measures are provided to the aircraft's state and route information. Stage 2 features two data collection activities and data are analyzed after each data collection activity to ensure that ASTOR aircraft in the scenario are free of initialization and route errors. Additionally, the AOPv.2-equipped ASTOR aircraft generate free-routes during the data collection activities, and those data are collected and converted to CPDLC Free Route messages for use in Stage 3.

The final stage (Stage 3) of the process allocates a percentage of aircraft to the "Free Route" category and assigns their respective CPDLC Free Route message to it in each scenario. Stage 3 results in integrated ASTOR-TMX scenarios, which are exercised in the simulation to verify TBO characteristics and assess variability between scenarios due to the non-deterministic nature of AOP trajectory solutions. Ten scenarios were created for use in IDO batch studies. Of those ten, six were chosen for Stage 3 evaluation to minimize data collection runtime and non-essential use of simulation resources.

4. Study Approach

An investigation of the simulation use case was developed as part of a structured, controlled approach to the initial exploratory study of a representative TBO environment for the 2040 timeframe. The approach detailed in this section provided a starting point to compare the simulation use case to present day operations and increased confidence in the reliability of data and results. The following subsections describe the experiment design, data collection, data analysis, and data validation aspects of the approach.

4.1 Design and Data Collection

The study had a repeated-measures design. Simulation runs of the selected scenarios were split into two types: baseline runs, implementing only the original fixed-routes, and TBO runs, implementing a mix of fixed-route and free-route flights in the same scenario. The same call signs appeared in the baseline and TBO runs so their data could be paired. Ten simulation scenarios were created to get a variety of flights over the course of two real-world traffic days. The order of the scenario numbering matches the chronological sequence under which each approximate timeframe occurred on their respective traffic day. From the ten scenarios created, six were chosen for use in this study. The six scenarios applied the same three time windows on each day, and these scenarios were selected so that traffic fluctuations occurring between time windows over the course of the day were captured. Table 2 below summarizes the experiment design of this study. With one baseline run and three TBO replicates per scenario, 24 runs were completed for each Stage 3 data collection activity.

Table 2: Experiment Design

Scenario Number	Traffic Day	Start Time (UTC)	Number of Runs (baseline + three TBO replicates)
2	05/23/2018	13:00	4
3	05/23/2018	15:00	4
4	05/23/2018	17:00	4
7	05/24/2018	13:00	4
8	05/24/2018	15:00	4
9	05/24/2018	17:00	4
			24 total runs

The TBO replicates in the simulation were run in a randomized order, since each of the simulation platforms featured in the use case contain non-deterministic elements that may influence the data analyses. The scenario run order is given in Table 3.

Table 3: TBO Replicate Run Order

TBO Replicate Order	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Scenario	4	9	8	3	2	2	3	4	3	9	4	7	7	9	8	7	2	8

Aircraft state data were collected for every flight. Latitude, longitude, altitude, fuel consumption, distance traveled, and time flown were recorded once a second for ASTOR aircraft and once every 30 seconds on average for TMX aircraft. The state data for each flight were summarized into three metrics of interest for this analysis:

- Total Fuel Burn, in pounds (lbs.);
- Flight Time, in seconds (s); and
- Flight Miles, in nautical miles.

4.2 Data Analysis Approach

There were two main goals of data analysis for this study: a) assess the benefits of a TBO environment compared to a baseline condition in terms of fuel burn, flight time, and flight miles, and b) understand the variability in the TBO environment. This section discusses the metrics used to analyze the data obtained from the simulation environment. The results for these metrics are presented in Section 5.

4.2.1 Benefits of a 2040 TBO Environment

To assess the benefits of a TBO environment, the metrics of interest were averaged together across the three TBO replicates for each flight. Averaging the replicates allows for a direct comparison with the baseline metrics. Differences were calculated by subtracting the baseline metric from the TBO metric for all corresponding flights. The starting hypotheses were that TBO flights saved fuel, saved time, and flew fewer miles than their baseline counterpart flights. Wilcoxon signed-rank tests[2] were used to test the hypotheses instead of the more commonly used t-test due to departures from normality in the data. Three additional tests were done on the subset of only free route flights, bringing the total number of hypothesis tests to six and therefore the Bonferroni corrected[3] significance threshold, alpha, to 0.05/6 = 0.0083.

4.2.2 Scenario Variability

Understanding the variability of the TBO environment was of interest with relation to future experiment design. Knowledge of variation between scenarios would help with choosing the number of scenarios needed for a future experiment. The inherent simulation variability in particular could influence the number of replicates. Understanding the spread in the metrics of interest also informs considerations that affect sample size and effect size. Furthermore, understanding the variation between scenarios provides the research team with information about which scenarios to include in future studies. For example, if one scenario was significantly different from the others, the research team may choose to either not include that scenario in future studies, or conduct further analyses to understand the intricacies of that scenario. Understanding what makes a particular scenario different from others may also assist in explaining simulation results.

Unlike the first goal of assessing benefits, this part of the analysis focuses only on the TBO environment; therefore the baseline runs were excluded and the replicates were not averaged together. One way to assess the variability from various sources is to build a model of each metric and create an analysis of variance table. Due to the repeated measures design (the TBO replicates) and nesting (unique flights appear within each scenario), mixed-effects models were used and variance estimates were taken from the random effects.

4.3 Data Validation

Data validation involved an iterative process of running simulations according to the experiment design matrix (Table 3), gathering output data, identifying simulation errors, manually inspecting errors, and implementing solutions until a final, acceptable set of data was realized. Validation of free route aircraft data in the final data set increased confidence in its correctness and in the authenticity of simulation characteristics observed. As a result, key insights gathered from data analysis became more closely reliant on the fidelity of the simulation system and uniqueness of the experimental setup. Details of the data validation process are provided in the following subsections.

4.3.1 Automated Identification of Simulation Errors

After all baseline and TBO replicate scenario runs were completed as part of a Stage 3 data collection, the output data for each free-route flight was run through an automated error detection process. Replicates were compared to baseline runs, as well as to each other, and flights with detected errors were flagged for manual inspection. Criteria for flagging by the automated process included large discrepancies found in lateral path, flight time, or altitude at termination; failure to climb or descend to assigned CPDLC altitude within a specified altitude range; failure to maintain an assigned CPDLC altitude for a minimum specified duration; and display of pilot model failures.

---

[2] The Wilcoxon signed-rank test is a nonparametric hypothesis test used to compare paired samples when the difference between pairs is non-normally distributed.

[3] A correction to the usual significance threshold of 0.05 is often used when carrying out multiple hypothesis test to keep the overall error rate low. The Bonferroni correction is one common example, where 0.05 is divided by the total number of tests and that number is used to determine significance for the individual tests.

4.3.2 Manual Inspection

Flights identified by the automated simulation detection process were manually inspected and separated according to the nature of error types observed. Classifications included false positives (i.e. flights erroneously flagged by the automated process), routes with confirmed simulation system errors (i.e., simulation system bugs or gaps in functionality), and routes resulting from operational errors (i.e., the simulation worked properly, but the CPDLC route instructions in the scenario file were not operationally realistic). False positives were retained in the data set, while operational and simulation errors were broken down further into outlier and repeatable error categories.

It is worth noting that during this part of the inspection process, effects from ATOS performance modeling (e.g., model fidelity, availability of suitable performance models, closeness-of-fit to the assigned model) were assumed negligible factors. Emphasis was placed on the general realism of flight performance in the simulation. Erroneous outlier flights that lacked operational realism or otherwise could not be properly characterized were manually removed from the data set. Repeated behaviors were categorized and addressed with technical solutions that were implemented and tested prior to another Stage 3 data collection iteration.

An issue identified during the data validation phase involved free route aircraft not achieving the step altitude assigned as part of the route clearance in the CPDLC message. Figure 4 presents an example comparison of the altitude profiles (in feet) over time (in seconds) of a background, fixed-route baseline flight and its three replicate free-route flights for the same scenario. The dashed horizontal line in each image represents the original cruise altitude, and the solid horizontal line represents the CPDLC step altitude provided by the early version of AOP v.2 in the TBO replicates. For this set of replicates, multiple errors were observed, including discrepancies between replicates (each replicate should be identical to one another), failure of two replicates to reach the CPDLC step climb altitude prior to descent, and the anomalous/undesirable simulation behavior of the third replicate. The high volume of background free-route flights enabled the removal of this flight from the final data set without adversely affecting the variability or other factors in the final analysis.

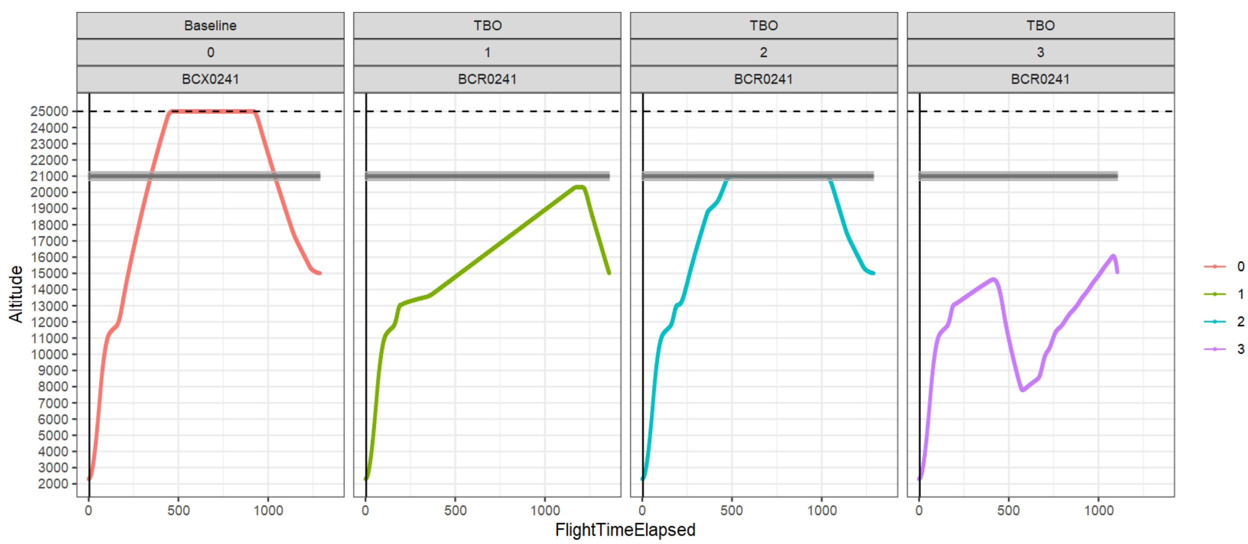

Figure 4: Example of flight with multiple simulation errors

4.3.3 Solution Implementation and Validation Output

Several solutions were implemented to address confirmed simulation and operational errors. In addition to the filtering and retention of false positives, and manual removal of poorly performing and outlier flights from the data set, technical corrections to simulation environment subsystems were implemented. Development activities primarily consisted of adjustments to the logic and ruleset of the ASTOR pilot model, and reruns[4] of particular scenarios with additional errors not captured by the automated error detection process. Adjustments made to the ASTOR pilot model minimized poor operational performance in free-route flights and other anomalies in baseline and fixed-route flights. A vetted and corrected data set primed for analysis was the output of the final iteration of the validation process.

5. Discussion of Results

For this research activity, six distinct simulation scenarios were selected from the ten TBO scenarios created using traffic from May 23-24, 2018. Each high-density scenario contains approximately 1500-1800 aircraft simulated in 3-hour time periods. Approximately 70% of the aircraft in each scenario are medium-high fidelity ASTOR simulated aircraft, and the remaining 30% are low-fidelity TMX simulated aircraft.

Data analyses confirmed that a majority of the ~40% of free-route aircraft, also referred to as TBO aircraft throughout the analyses, had fuel- and time-savings. Furthermore, the variability between scenarios was minimal, which allows future research activities to utilize these scenarios without concern for effects due to the scenario chosen. This section provides the results and statistical analyses for the study.

5.1 Scenario Traffic Summary

The final data set for analysis contained 38,592 distinct flights. Table 4 shows the number of flights in each scenario's baseline run. The number of flights in each three-hour window increased during each traffic day with scenarios 4 and 9, which spanned 17:00 to 20:00 UTC, having the most flights for each day.

Table 4: Baseline Flight Count by Scenario

Scenario	Flight Count
2	1492
3	1546
4	1766
7	1503
8	1563
9	1783

The flights in each scenario were sorted into different categories (e.g., background traffic, free route, ASTOR compatible[5]) and their call sign was generated accordingly. Table 5 lists the flight type categories, and Figure 5 shows the proportion of flight types within each TBO scenario, with the length of the bar showing the total number of flights for one TBO run.

---

[4] Note: Reruns of a given scenario did not affect the TBO replicate run order presented in Table 3.

[5] "ASTOR Compatible" aircraft are those that can be mapped to an ASTOR Airframe performance model (e.g., BCR, BCX, TCR, and TCX). "ASTOR Non-Compatible" aircraft are those that can only be modeled using TMX (e.g., BNX and TNX).

Table 5: Flight Type Categories

Call Sign Prefix	Flight Type
BCR	Background ASTOR, free route
BNX	Background TMX, fixed route
BCX	Background ASTOR, fixed route
TCR	Traffic of interest, ASTOR, free route
TNX	Traffic of interest, TMX, fixed route
TCX	Traffic of interest, ASTOR, fixed route

Background traffic (BCR + BNX + BCX) make up about 75% of the flights in each TBO scenario and traffic of interest (TCR + TNX + TCX) make up the other 25%. Just over 30% of flights were simulated in TMX (BNX + TNX) while the rest were simulated with ASTOR aircraft. A complete flight count summary can be found in Table A1 in the appendix.

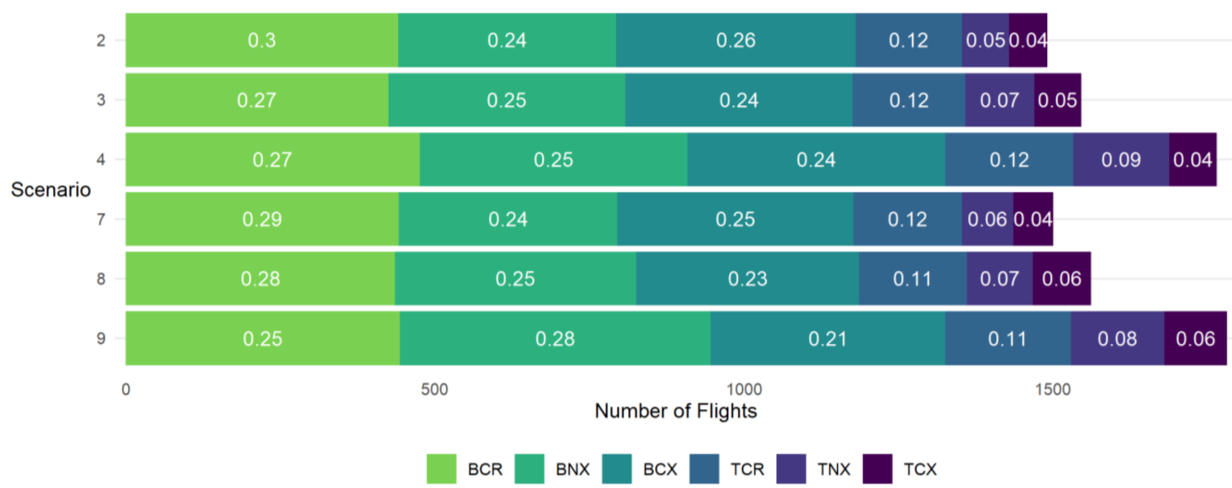

Figure 5: Proportion of flight types by TBO scenario

In the TBO runs, about 40% of the flights flew free routes (~30% BCR's + ~10% TCR's) and approximately 60% are on fixed routes. The goal of the TBO scenarios was a mixed equipage of services – 60% advanced-services equipped aircraft (i.e., "free route" aircraft) and 40% baseline equipage (i.e., "fixed route" aircraft). The goal for this use case was not met for a number of reasons. First, the number of Traffic of Interest aircraft on the selected days and time from the SWIM data was less than anticipated. Second, limitations in the availability of ASTOR performance models to apply to the aircraft within the SWIM data, combined with missing or incomplete SWIM data, caused several TCR and BCR aircraft to revert to TNX and BNX aircraft. Third, some advanced-services equipped aircraft were determined to be on an optimal route; therefore, no optimized free route was generated for this aircraft. Finally, the removal of aircraft from the simulation during the scenario generation process and during post-hoc data validation analyses lowered the number of potential free route traffic.

5.2 Benefits of TBO

To assess the benefits of a TBO environment, fuel burn, flight time, and flight miles from TBO flights were compared with their corresponding baseline flights. The following sections present results of analyses related to these three metrics. Furthermore, analyses comparing airspace coverage (i.e., what areas were traversed by the aircraft in the scenario) for the TBO scenarios versus the baseline scenarios are presented. Airspace coverage was used to measure airspace flexibility.

5.2.1 Fuel Burn

The difference in total fuel burn was calculated by subtracting the baseline fuel burn from the TBO-averaged fuel burn for all corresponding flights. Negative values indicate the TBO flight saved fuel, and the starting hypothesis was that TBO flights saved fuel compared to baseline.

The differences in fuel burn ranged from -1,727.55 to 2,917.59 pounds with a median difference of -0.002 pounds across all flights. Figure 6 shows a histogram of values for difference in fuel burn, with individual points showing the lower and upper 0.5% of values. The middle 99% percent of data fell between -240.2 and 259.8 pounds and the remaining 1% are shown as the circles along the x-axis. The peak in the middle represents approximately 58% of flight pairs (5,575 out of 9,653) with fuel differences between -10 and 10 pounds Only three flight pairs had exactly no difference in fuel burn between the baseline and TBO runs.

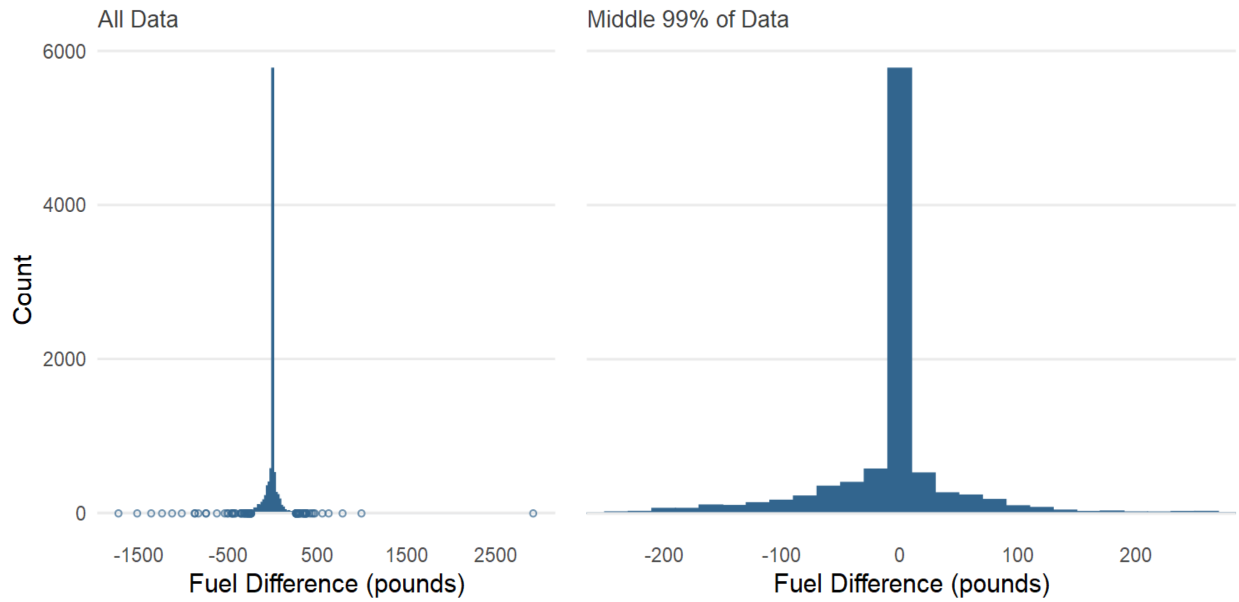

Figure 6: Fuel Burn Difference for All Aircraft in All Scenarios

The fuel burn difference was not normally distributed as shown in the normal quantile-quantile (Q-Q) plot in Figure 7. Ideally, the points would form a generally straight diagonal line to indicate similarity with a normal distribution. Therefore, the departure from normality was dramatic enough to conduct a non-parametric test instead of a typical paired t-test. The Wilcoxon signed-rank test was appropriate for this type of data. To test the difference in medians between groups, paired differences were calculated then ranked in order and the signs of the ranks are summed. The median fuel burn in the baseline runs was 1,400.03 pounds, while the median in the TBO runs was 1,370.76 pounds. A one-sided Wilcoxon signed-rank test showed that the difference was statistically significant ($Z = 20834207$, p-value < 0.001), therefore it was concluded that TBO flights consumed less fuel than baseline flights.

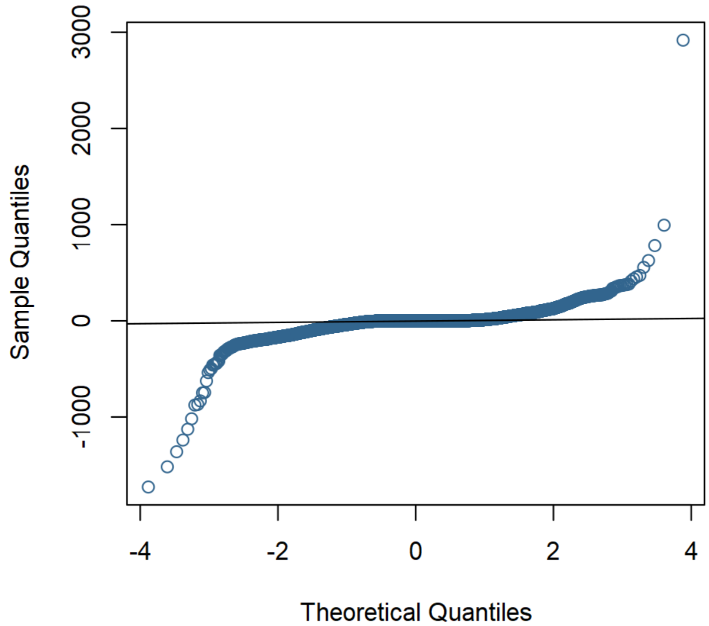

Figure 7: Normal Q-Q Plot of Fuel Burn Difference for All Aircraft in All Scenarios

The fuel burn values were mostly driven by two factors: whether the flight was on a fixed or free route, and whether the flight was considered background traffic or traffic of interest. Table 6 gives a breakdown of the fuel burn differences for the intersection of flight types as well as marginal totals for each factor. Flights in the traffic of interest category that flew free routes saw the highest benefit with a median fuel savings of 37.53 pounds over baseline. Background traffic that flew free routes saw fuel savings of 9.27 pounds compared to baseline on average. As expected due to the setup of the simulation, fixed route flights followed their trajectories while ignoring all other aircraft, and saw no fuel savings regardless of traffic type. Figure A1 in Appendix A shows the distribution of fuel differences as histograms, broken down by traffic type, either background or traffic of interest, and by the route of the TBO flight, either free or fixed.

Table 6: Fuel Burn Differences by TBO Route Type and Traffic Type, in pounds

Traffic Type	TBO Route Type				*Overall*	
	Free Route		Fixed Route			
	Median Difference	Number of Flights	Median Difference	Number of Flights	*Median Difference*	*Number of Flights*
Traffic of Interest	-37.53	1117	0.002	1158	***-0.043***	***2275***
Background	-9.27	2667	0.002	4711	***-0.001***	***7378***
Overall	***-17.18***	***3784***	***0.002***	***5869***	***-0.002***	***9653***

Focusing on only free route flights, the distribution of fuel burn difference is shown in Figure 8. The minimum fuel burn difference in the free routes was -1,727.55 and the maximum was 994.21 pounds, with 99% of the data falling between -364.18 and 312.81 pounds. The median fuel difference was -17.18 pounds.

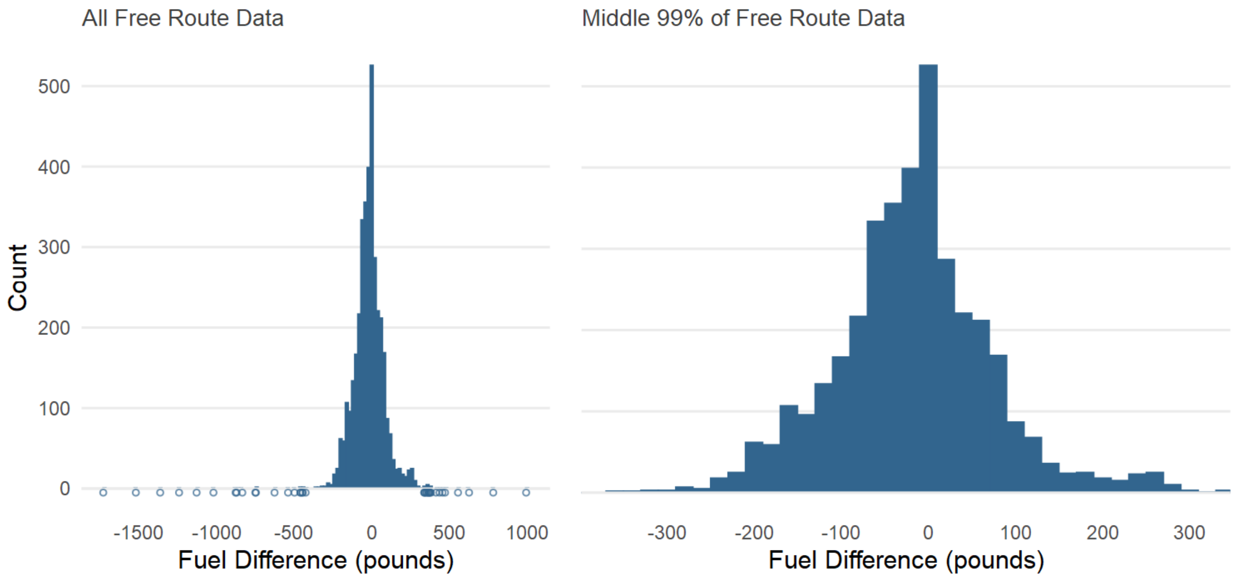

Figure 8: Fuel Burn Difference for All Free Route Flights in All Scenarios

As shown in Figure 9, the data were not normally distributed. Although there was no extreme peak in the middle, the tails were unbalanced. The departure from normality necessitated a non-parametric test instead of a typical paired t-test. A one-sided Wilcoxon signed-rank test showed a significant difference in fuel burn between TBO free routes and their baseline counterparts ($Z = 2664144$, p-value < 0.001). The median fuel burn for free routes was 1,471.95 pounds while the corresponding baseline median was 1,548.29 pounds.

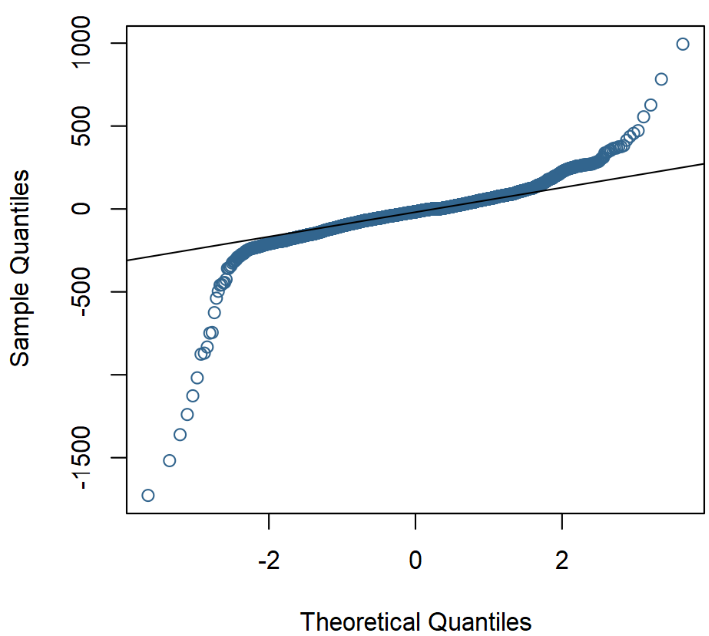

Figure 9: Normal Q-Q Plot for Fuel Burn Difference for All Free Route Flights in All Scenarios

Figure 10 and Table 7 summarize the fuel burn differences of free routes by aircraft type. The individual points in Figure 10 show the lower and upper 0.5% of values. The majority of free route aircraft were

NASA_HU25 ATOS model aircraft types and saw fuel savings averaging more than 30 pounds over the baseline; however, the other aircraft types saw a wider range of values that tended to see no savings or even increased fuel burn.

Because aircraft represented by the NASA_HU25 model share similar mission profiles that tended to be shorter regional flights, they were able to realize most of the predicted fuel benefit during the scope of the simulation. Aircraft types represented by the NB172_2E27 model showed almost no difference in fuel burn on average, but demonstrated a wide range of values. This could be due to the large variability in the mission profiles, ranging from regional to transcontinental flights, or due to the variety of performances that were mapped to the NB172_2E27 model type. Aircraft types represented by the NB250_2E40, WB315_2E48, and WB535_2E77 models had the lowest savings or burned excess fuel compared to baseline. These only accounted for about 6% of free route aircraft and tended to be transcontinental or international flights meaning they did not fly long enough in the simulation to achieve their predicted fuel benefits. All ATOS model types presented in Table 7 map to the airframe types listed in Appendix E.1 in [17].

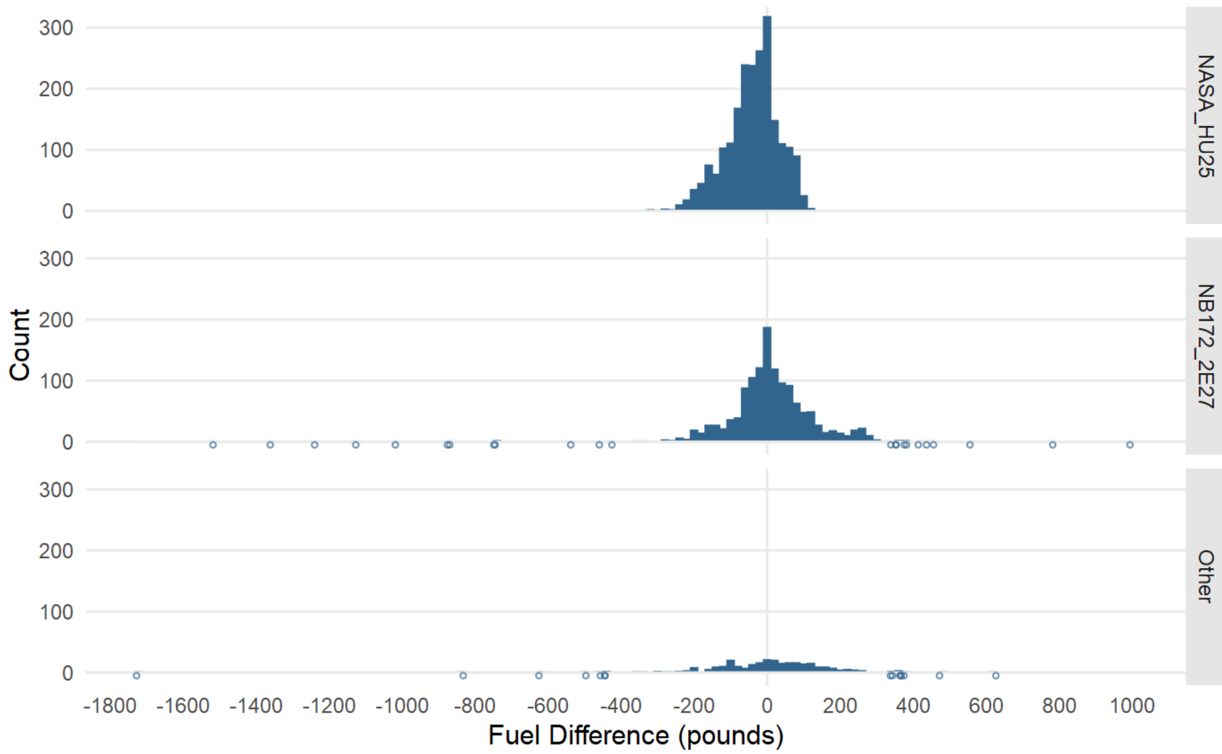

Figure 10: Fuel Burn Difference by Aircraft Type for All Scenarios

There is evidence to conclude TBO flights save fuel compared to baseline. When the free routes that had the benefits of AOP were grouped with all flights, there was still a significant difference compared to baseline (p-value < 0.001). Diving further into the fuel savings showed where the most savings occurred: traffic of interest tended to save more fuel than background traffic, and NASA_HU25 model types saw the highest savings with a median of 32.55 pounds of fuel savings.

Table 7: Free Route Fuel Burn Difference Statistics by Aircraft Type, in pounds

ATOS Model	Mean	Median	Standard Deviation	Minimum	Maximum	Number of Flights
NASA_HU25	-39.96	-32.55	71.44	-318.40	115.47	2171
NB172_2E27	7.95	2.40	144.94	-1517.77	994.21	1331
WB315_2E48	8.42	26.46	257.27	-1727.55	626.81	103
NB137_2E22	2.48	17.66	107.89	-496.51	180.49	72
NB250_2E40	-22.71	1.65	135.83	-625.20	363.42	70
WB535_2E77	25.22	40.58	190.65	-445.61	472.22	37
Overall	***-20.03***	***-17.18***	***116.42***	***-1727.55***	***994.21***	***3784***

5.2.2 Flight Time

The same analysis performed to analyze fuel burn was performed on total flight time. The difference between baseline and the averaged TBO flight times were calculated for every flight pair and negative values indicate the TBO flight saved time. The initial null hypothesis was that TBO flights had equal or greater flight time compared to baseline while the alternative hypothesis was that TBO flights saved time.

The difference in flight time elapsed between TBO flights and their baseline counterparts had a median of 0.0 seconds with a range of -997.33 to 646 seconds. Figure 11 shows the distribution of flight time differences with the lower and upper 0.05% of values represented by points along the line y = 0. The middle 99% of values fell between -297 and 192.48 seconds, or about -5 minutes to 3 minutes. The peak around zero in the plot below contains 6,748 flights between -10 and 10 seconds, with 3,007 flights at exactly 0 seconds difference between baseline flight time and TBO flight time[6].

These values are not normally distributed as shown in the normal Q-Q plot in Figure 12. The Wilcoxon signed-rank test ignores the ties at zero but with the remaining data it showed a significant difference between baseline and TBO flight times (Z = 7790309, p-value < 0.001). The median baseline flight time was 1,967 seconds, about 32 minutes and 47 seconds, and the TBO flight time median was 1,948 seconds, or about 32 minutes and 28 seconds. The results of this one-sided test provide evidence that TBO flights had shorter flight times than baseline; however, the differences tended to be only a few seconds of savings.

[6] Note: The large frequency of zero second differences was caused by the simulation's data recording rate. Fractional seconds of savings (e.g., 0.3 seconds) were counted as zero seconds.

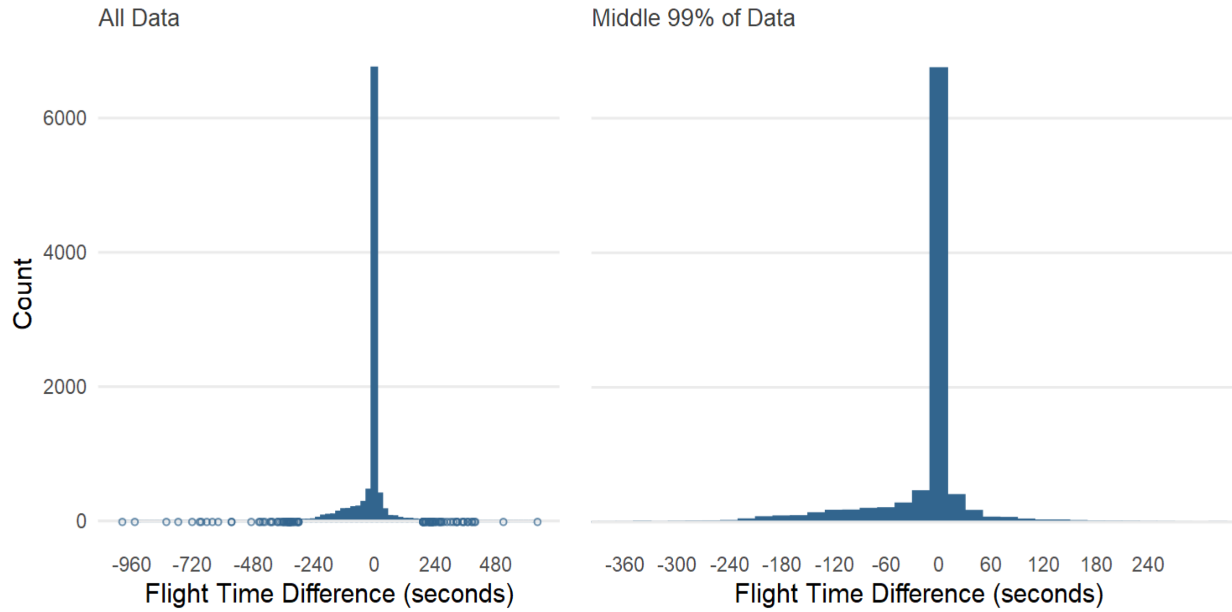

Figure 11: Flight Time Difference for All Aircraft in All Scenarios

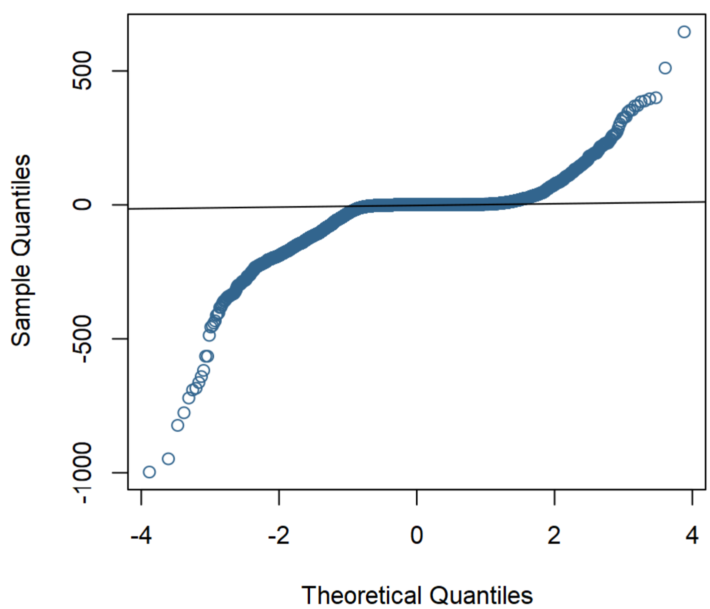

Figure 12: Normal Q-Q Plot of Flight Time Difference for All Aircraft in All Scenarios

The flight time values were mostly driven by two factors: whether the flight was on a fixed or free route, and whether the flight was considered background traffic or traffic of interest. Table 8 provides a breakdown of the flight time differences for the intersection of flight types as well as marginal totals for each factor. Figure A2 in Appendix A shows the histograms at the intersections, margins of traffic types and route types, and summarizes the distributions. Background traffic that flew free routes saved the most time; these flights experienced a median time savings of 16 seconds.

Table 8: Flight Time Differences by TBO Route Type and Traffic Type, in seconds

Traffic Type	TBO Route Type				*Overall*	
	Free Route		Fixed Route			
	Median Difference	Number of Flights	Median Difference	Number of Flights	*Median Difference*	*Number of Flights*
Traffic of Interest	0.000	1117	0.000	1158	***0.000***	***2275***
Background	-16.00	2667	0.000	4711	***0.000***	***7378***
Overall	***-7.000***	***3784***	***0.000***	***5869***	***-0.002***	***9653***

The distribution of flight time difference for only free routes is shown in Figure 13. There is still a peak around 0 seconds of flight time difference, but the median was -7 seconds. The middle 99% of data fell between -359.51 and 213.51 seconds, about -6 minutes to 3.5 minutes.

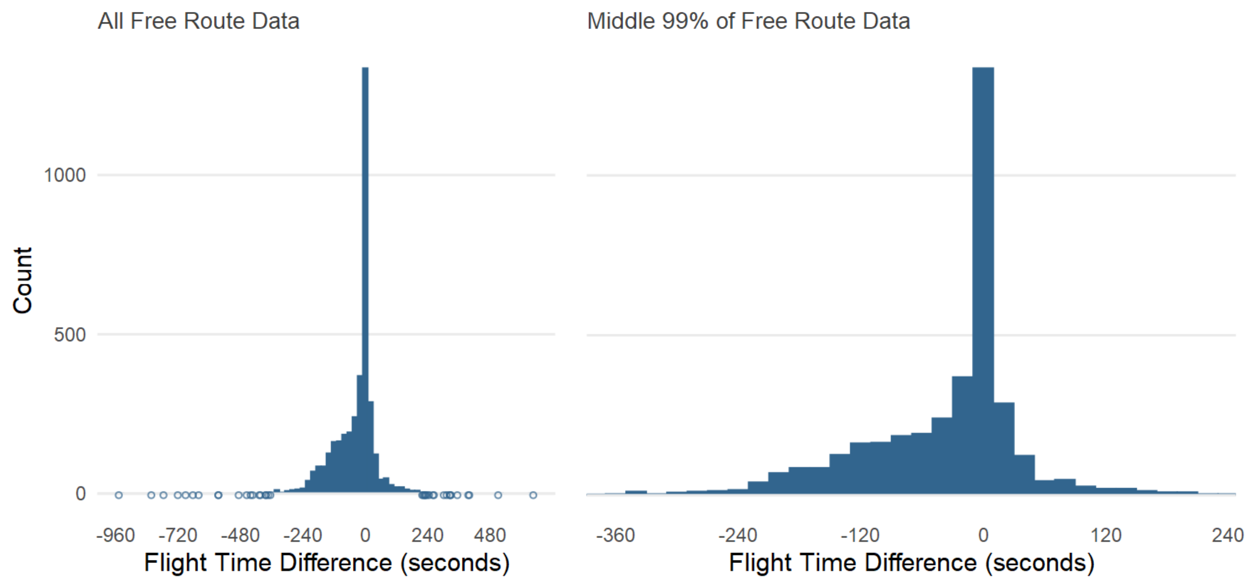

Figure 13: Flight Time Difference for All Free Route Flights in All Scenarios

These data were not normally distributed, as seen in Figure 14. The departure from normality necessitated a non-parametric test instead of a typical paired t-test. A one-sided Wilcoxon signed-rank test provided evidence that free routes saved time compared to their baseline ($Z = 981293$, p-value < 0.001). The median free route flight time was 2,022.67 seconds while the baseline median was 2,089.5 seconds, a difference of a little over a minute.

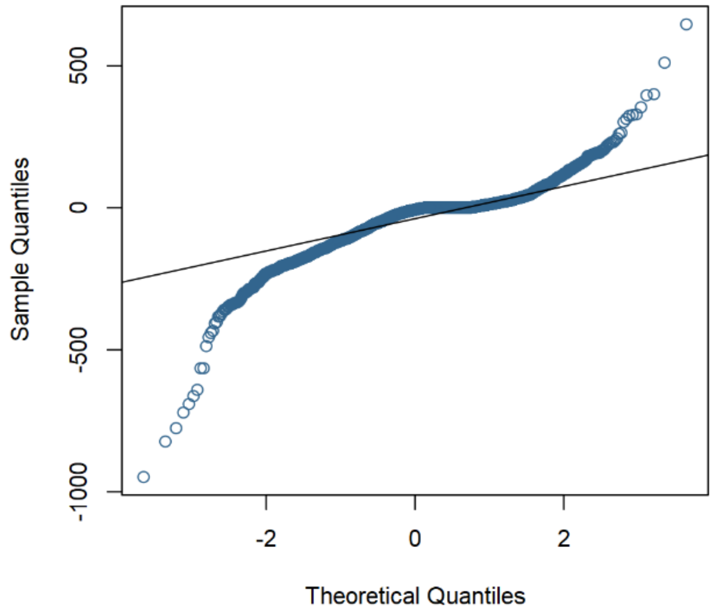

Figure 14: Normal Q-Q Plot for Flight Time Difference for All Free Route Flights in All Scenarios

The different aircraft types experienced differences among time savings as summarized in Table 9 and Figure 15. The individual points in Figure 15 show the lower and upper 0.5% of values. The NASA_HU25 aircraft type tended to save more time than any other aircraft type, these jets had a median free route flight time difference of -55 seconds while no other type saw a negative median. As was the case with fuel burn, the aircraft mapped to the NASA_HU25 model were comprised of shorter flights that were able to realize the benefits of the free route during the course of the simulation while other types tended to be much longer flights that may not have had the chance to experience benefits.

Table 9: Free Route Flight Time Difference Statistics by Aircraft Type, in seconds

ATOS Model	Mean	Median	Standard Deviation	Minimum	Maximum	Number of Flights
NASA_HU25	-73.49	-55.0	78.67	-456	313.0	2171
NB172_2E27	12.83	0.0	82.60	-948	646.0	1331
WB315_2E48	-13.86	0.0	83.30	-691	148.0	103
NB137_2E22	31.80	17.2	66.13	-25	400.0	72
NB250_2E40	0.11	0.0	38.31	-250	133.5	70
WB535_2E77	14.26	0.0	47.88	-134	193.0	37
Overall	***-37.28***	***-7.0***	***89.78***	***-948***	***646.0***	***3784***

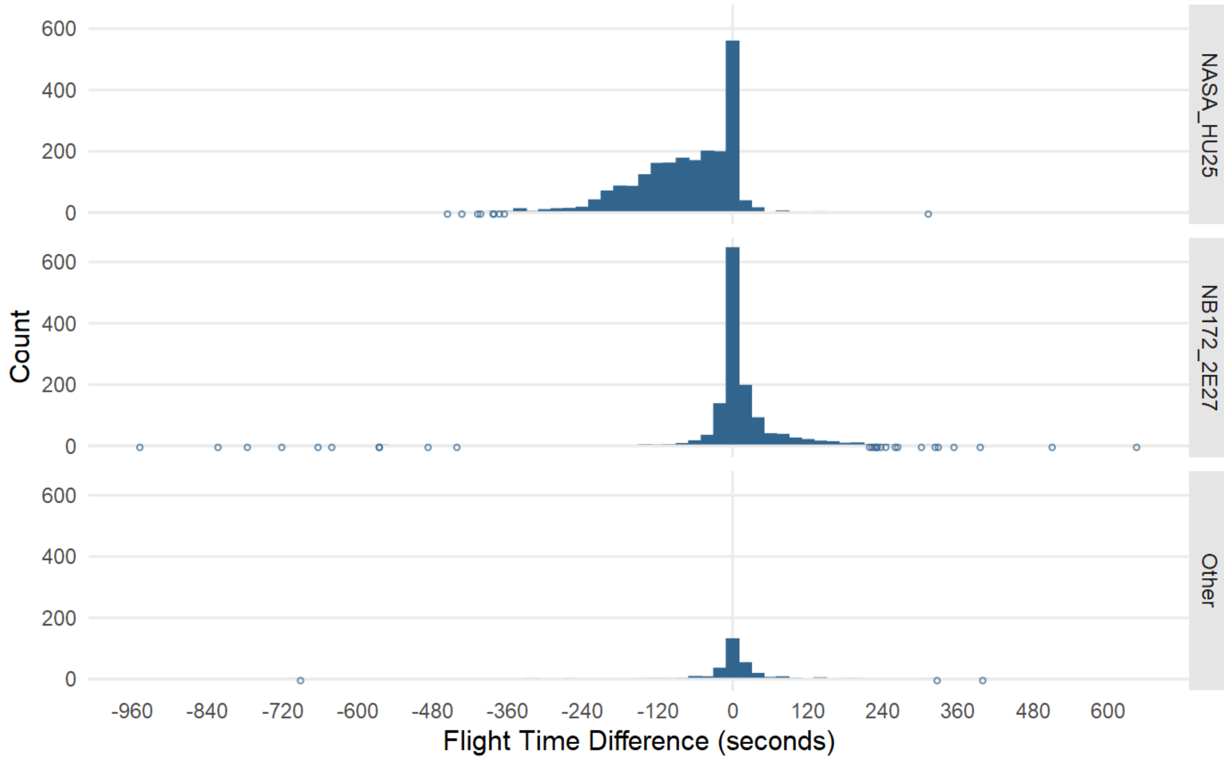

Figure 15: Flight Time Difference by Aircraft Type for All Scenarios

There is evidence that flight time was reduced by free routes, and enough flights saved time that when combined with all data, a significant difference was still found (p-value < 0.001). Larger time savings were found in background free routes (median savings of 16 seconds) and by NASA_HU25 aircraft (median savings of 55 seconds). Additionally, savings in fuel burn and flight time did not always coincide; about 13% of free route flights that saved time did not save fuel and 18% that saved fuel did not save time. Simply reducing flight time was not the only mechanism by which fuel savings were observed.

5.2.3 Flight Miles

Cumulative nautical miles flown by each flight were compared between baseline and averaged TBO runs. A negative flight mile difference meant that the TBO flight flew fewer miles than the baseline. The initial hypothesis was that TBO flights would see fewer miles flown than baseline on average.

The median difference in flight miles between baseline and TBO flights was 0.004 nautical miles. Differences varied from a minimum of -117.03 to a maximum of 72.12 nautical miles; however, the middle 99% of data fell between -9.77 and 16.59 nautical miles. The remaining 1% are shown as points along the x-axis in Figure 16. The bar around 0 nautical miles contains 7,949 flights between -0.5 and 0.5 nautical miles, where only eight flights had a flight mile difference of exactly zero nautical miles.

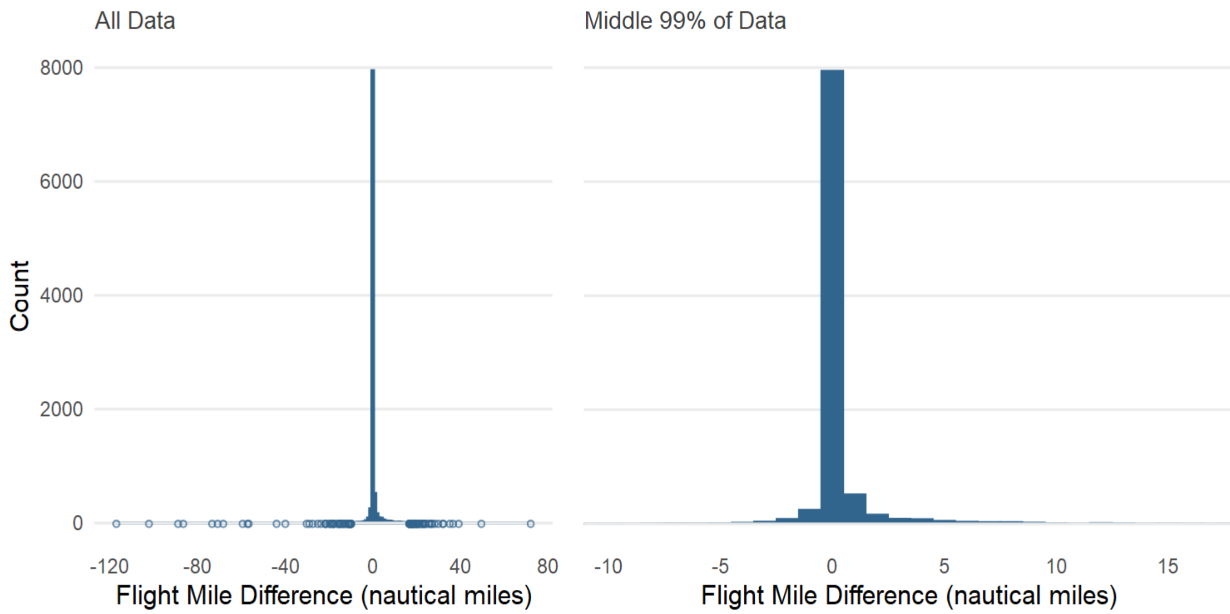

Figure 16: Flight Miles Difference for All Aircraft in All Scenarios

This data did not appear to come from a normal distribution as shown in the normal Q-Q plot in Figure 17. The departure from normality necessitated a non-parametric test instead of a typical paired t-test. A one-sided Wilcoxon signed-rank test indicated no difference between TBO and baseline flights (Z = 29329637, p-value = 1). The median distance flown in baseline flights was 217.6 nautical miles and the median TBO distance was 218.15 nautical miles.

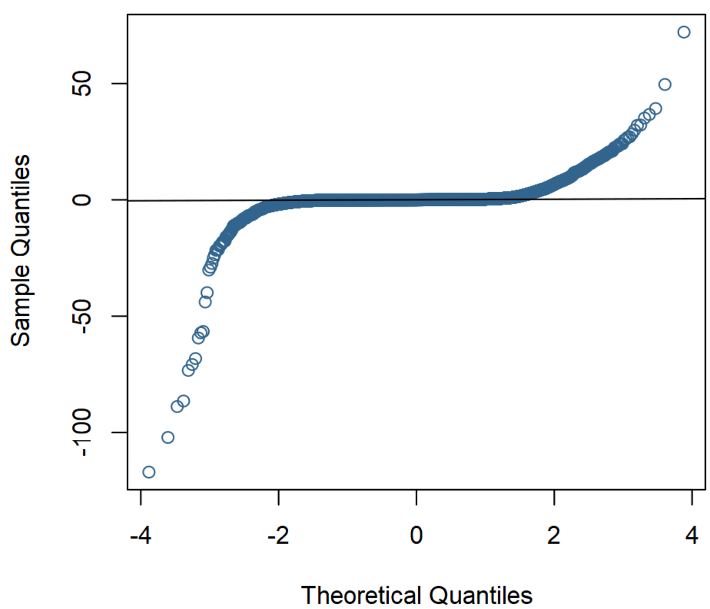

Figure 17: Normal Q-Q Plot of Flight Miles Difference for All Aircraft in All Scenarios

Table 10 shows the breakdown of the difference in flight miles by route type and traffic type. Figure A3 in Appendix A shows the histograms at the intersections and margins of traffic types and route types and summarizes the distributions. Free routes showed a small increase in flight miles traveled on average, with traffic of interest accounting for more flight miles than background traffic (median difference of 0.229

nautical miles compared to 0.072 nautical miles for background traffic). Because traffic of interest tended to contain longer flights that crossed ZOB, there was an opportunity for extra distance to accumulate along the route due to trajectory changes.

Table 10: Flight Mile Differences by TBO Route Type and Traffic Type, in nautical miles

Traffic Type	TBO Route Type				*Overall*	
	Free Route		Fixed Route			
	Median Difference	Number of Flights	Median Difference	Number of Flights	*Median Difference*	*Number of Flights*
Traffic of Interest	0.229	1117	0.000	1158	**0.019**	***2275***
Background	0.072	2667	0.000	4711	**0.003**	***7378***
Overall	***0.099***	***3784***	***0.000***	***5869***	***0.004***	***9653***

When only looking at free routes, as shown in Figure 18, the median difference in flight miles was 0.099 nautical miles. Ninety-nine percent of free route flights saw a flight mile difference between -17.67 and 21.78 nautical miles compared to baseline.

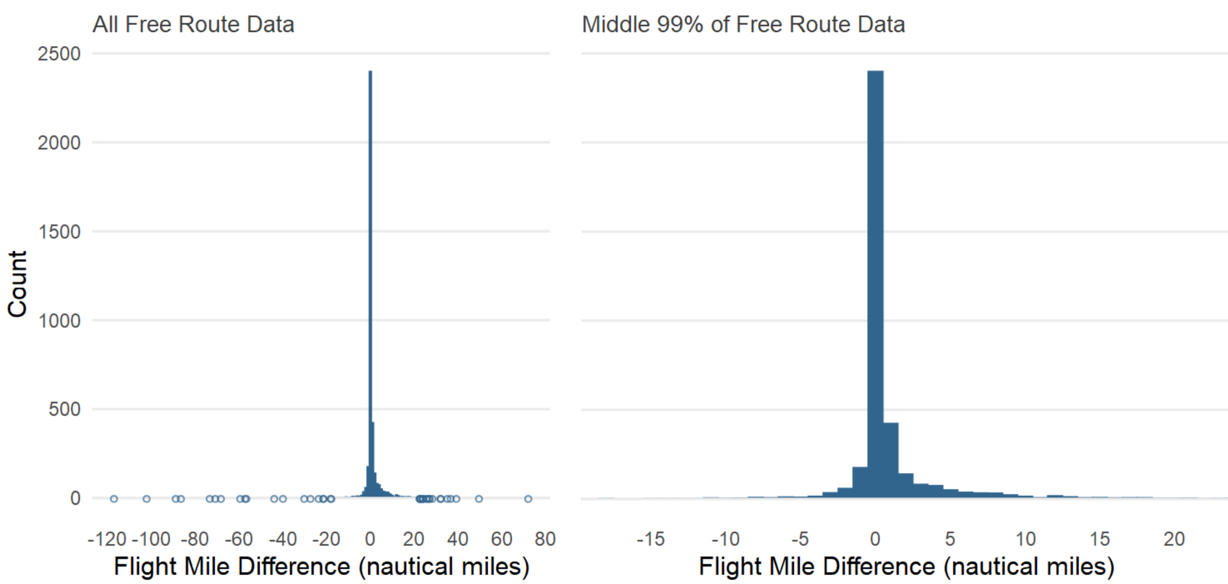

Figure 18: Flight Miles Difference for All Free Route Flights in All Scenarios

Since the distribution of differences does not meet the normality assumption, as seen in Figure 19, a one-sided Wilcoxon signed-rank test was conducted. There was no significant difference between free route flights and their baseline counterpart in terms of distance flown (Z = 5330231, p-value = 1). The free route TBO flight median was 231.06 nautical miles compared to 229.27 nautical miles among the corresponding baseline flights. In fact, a follow-up test with the alternative hypothesis flipped to state that TBO flights flew further than baseline showed evidence to support that hypothesis (Z = 5330231, p-value < 0.001). Since AOP v.2 was selected to optimize flights to save fuel and not time nor along-path distance, the results of this analysis are expected.

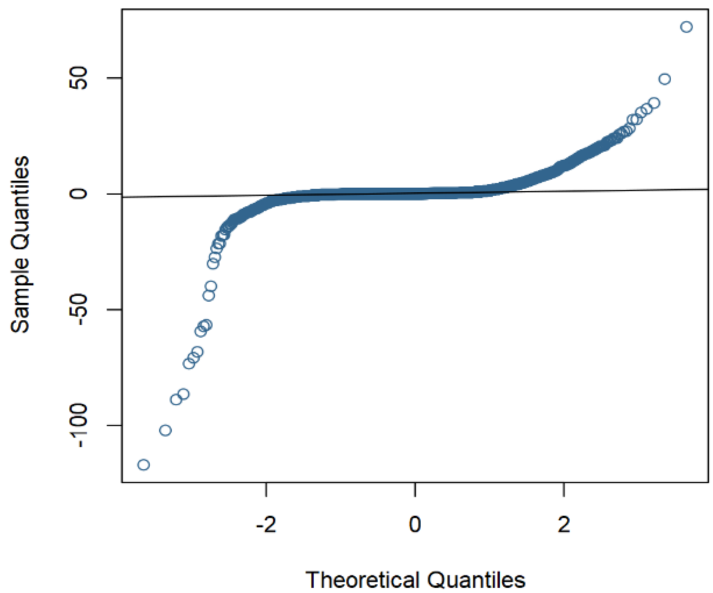

Figure 19: Normal Q-Q Plot for Flight Miles Difference for All Free Route Flights in All Scenarios

The median flight mile difference for free routes was very similar for all aircraft types, as summarized in Table 11 and Figure 20. The distributions were all centered on zero but some types had a larger range of values, like the NB172_E27, where some of the miles saved could have come from an opportunity to make lateral shortcuts through ZOB. Alternatively, shorter regional flights may not have had the same lateral flexibility during the simulation.

Table 11: Free Route Flight Mile Difference Statistics by Aircraft Type, in nautical miles

ATOS Model	Mean	Median	Standard Deviation	Minimum	Maximum	Number of Flights
NASA_HU25	0.98	0.07	3.58	-23.57	35.17	2171
NB172_2E27	0.20	0.19	8.18	-117.03	72.12	1331
WB315_2E48	0.30	0.41	9.59	-73.32	26.90	103
NB137_2E22	0.96	0.16	2.96	-5.22	14.37	72
NB250_2E40	0.47	0.30	4.32	-30.17	12.36	70
WB535_2E77	1.51	0.14	5.42	-18.18	18.99	37
Overall	***0.68***	***0.10***	***5.86***	***-117.03***	***72.12***	***3784***

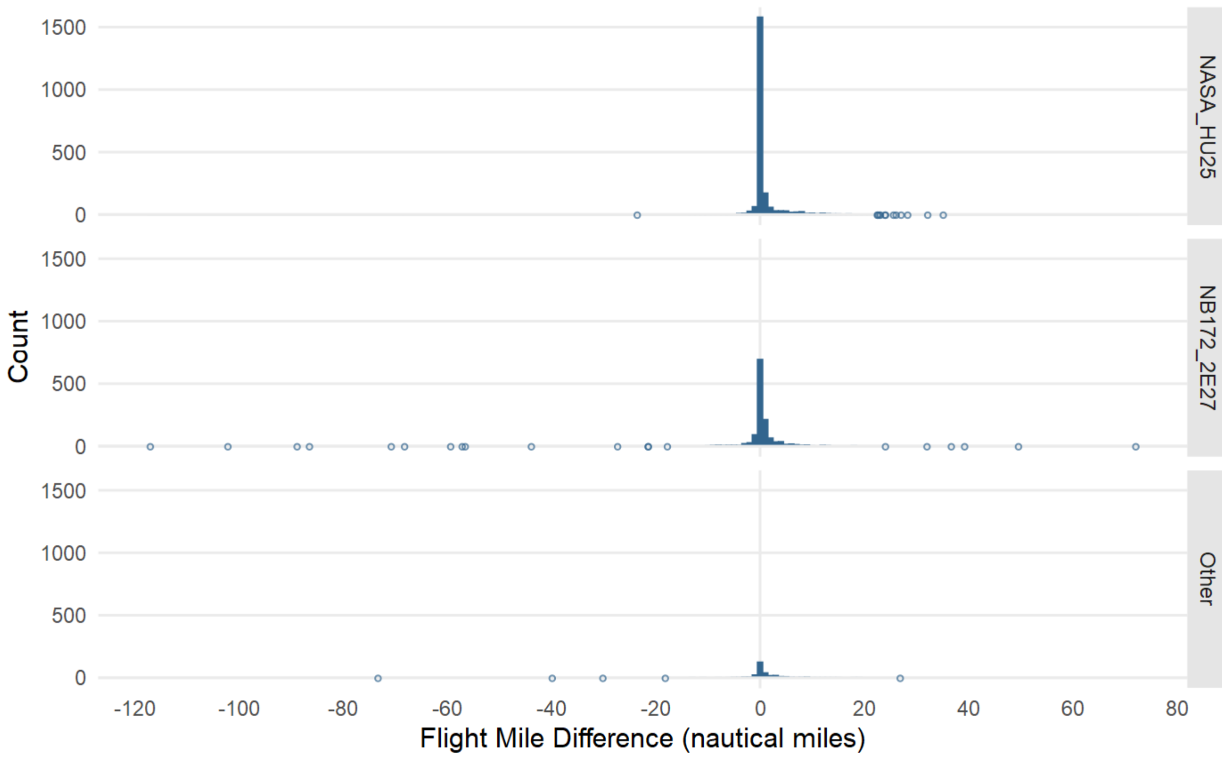

Figure 20: Flight Miles Difference by Aircraft Type for All Scenarios

5.2.4 Airspace Coverage and Structure

Airspace coverage was calculated by applying a rectangular grid around ZOB where each cell is 0.5 square nautical miles. The proportion of cells that contained the flight path of at least one flight was calculated for all four runs of each scenario. The average coverage in baseline scenarios was 69.0% while the average coverage was 70.2% for TBO scenarios, but the difference was not statistically significant (p-value = 0.2).

Although the TBO runs did not expand flights into unused territory on average, the concentrated areas in the baseline airspaces did see dispersion in the TBO airspaces. Figure 21 shows two heat maps from Scenario 4. The top map is the baseline run, which had 71.5% coverage, and the bottom map is the first TBO replicate run, which had 72.3% coverage. The heat maps show the counts of flights that pass within each 0.5 square nautical mile cell, with a Gaussian blur for easier visualization. There are east-west structures in yellow as well as highly traveled areas in blue that dissipate when going from the baseline to TBO run.

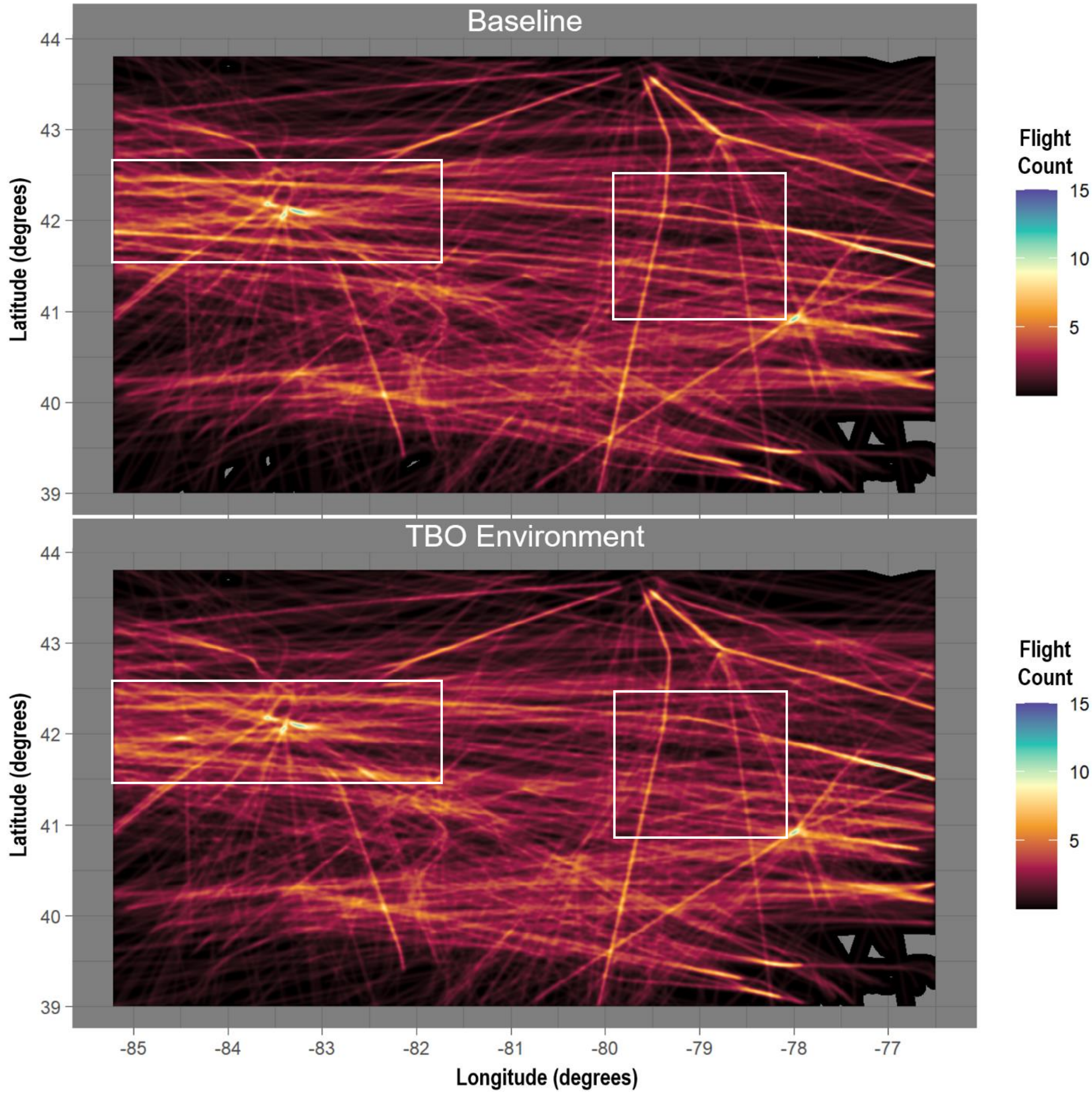

Figure 21: Flight Count Heat Maps, Scenario 4

The rectangles on the left in both maps of Figure 21 highlight an area where two east-west route structures in the baseline run tend to dissipate in the TBO run. The blue regions within that rectangle around 42 to 42.5 degrees latitude and -83 to -84 degrees longitude are likely due to traffic flowing in and out of Detroit Metropolitan Wayne County Airport, which is located at 42.22 and -83.36 degrees. The rectangles on the right show an area with the same two east-west routes at their intersection with two dominant north-south routes, which forms a cross hatching pattern in the baseline run that disappears in the TBO run, just leaving the north-south routes.

To highlight changes between the baseline and TBO heat maps, the difference between the baseline and TBO flight counts was calculated per cell and plotted. Prominent flight count differences are shown in

Figure 22. The areas in orange and red show where more baseline flights occurred and the blue areas show where more free-route flights traveled in the TBO environment.

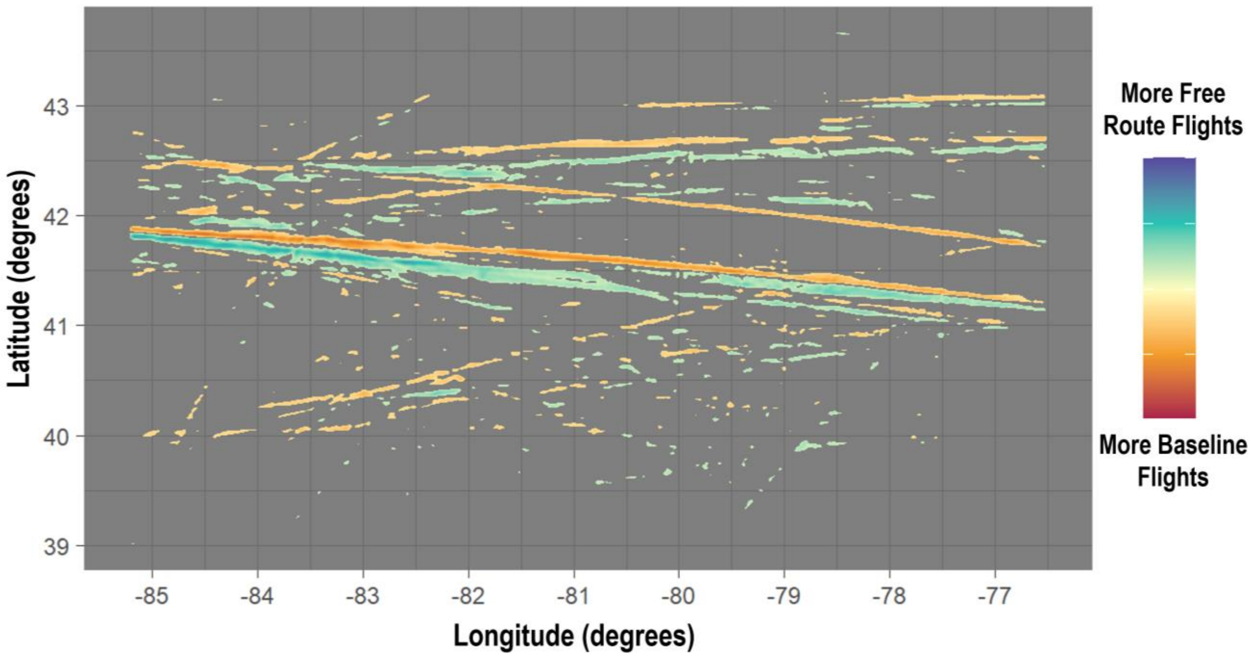

Figure 22: Flight Count Heat Map Highlighting Prominent Trajectory Differences between TBO and Baseline Environment, Scenario 4

This plot shows two ways that flights changed between baseline and TBO runs. First, a shift in the route location from baseline to TBO is indicated when an orange route is accompanied by a blue route nearby. For example, the east-west lines through the middle of ZOB show that the free routes in this scenario tended to fly a more southern route than the baseline fixed routes. The second indication of how flights differed in the TBO environment is when orange areas lack nearby blue areas, meaning free routes took different paths from baseline as well as each other. This can be seen in the spotted area in the southwest part of the plot. The results presented for Scenario 4 are representative of all of the TBO scenarios examined.

5.3 Variability in the TBO Environment

Understanding the variability in the data can provide context to the analysis results discussed for this study as well as inform the design of future studies. The data used in the variability analysis was from TBO runs only and no comparisons were made to the baseline. The same metrics of fuel burn, flight time, and flight miles were used to assess variability. Figure 23 shows the distribution of each metric for all TBO flights, including all three replicates.

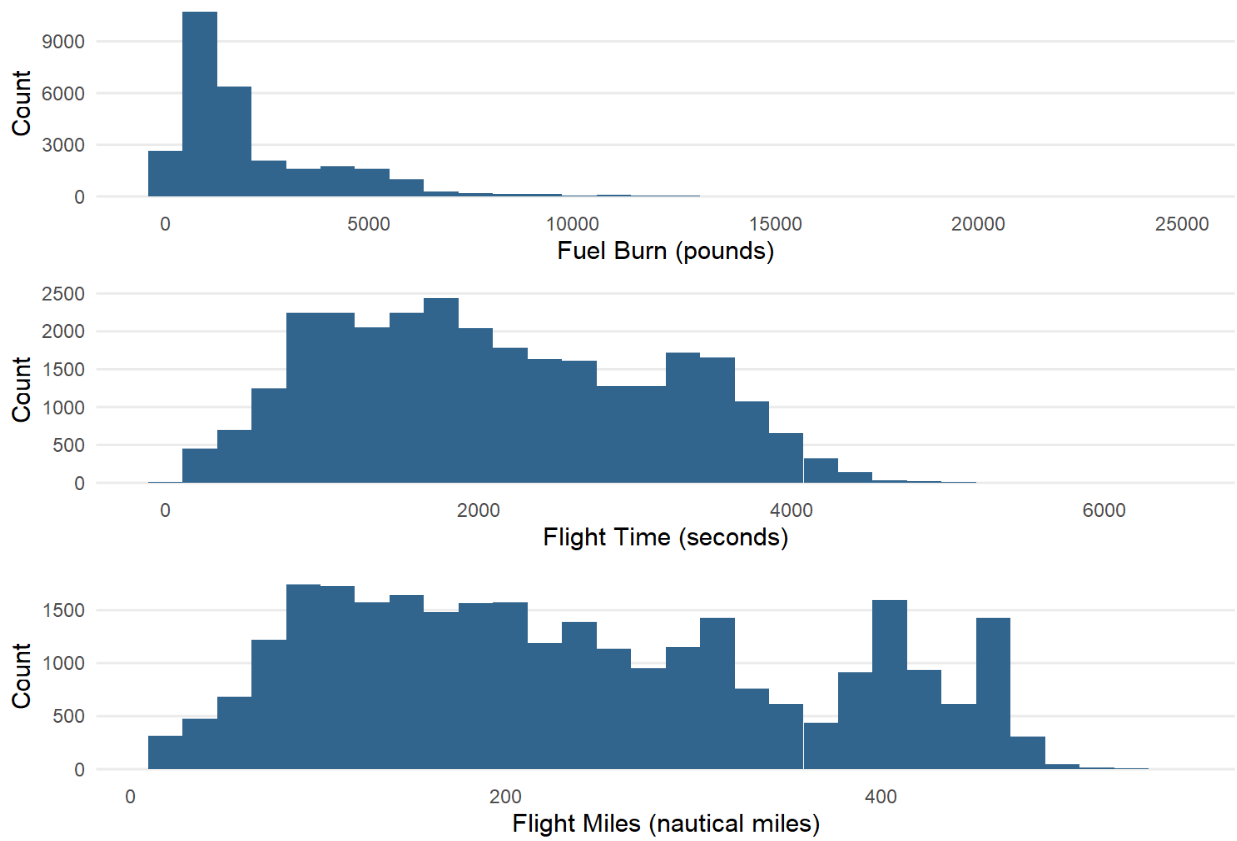

Figure 23: Fuel Burn, Flight Time, and Flight Miles for All Aircraft in All TBO Scenarios

These plots show the wide range of values seen in the data for each metric. The goal of the following analysis is to determine what the largest contributing factors are to the variation in these metrics.

5.3.1 Sources of Variability

Several possible sources of variability can be pulled from the setup of the experiment, including scenarios, replicates, and fixed vs. free routes. Each flight in the simulation also had unique characteristics that contributed to the resulting fuel burn, flight time, and distance flown. The performance model, route flown, starting weight, and traffic type (background traffic or traffic of interest, as described in Section 3.2) are some examples. The performance model of each flight explains a large portion of the variability between flights, especially for fuel burn. There were 136 unique performance models represented in the simulation, which were grouped into weight classes designated by the FAA [40]. Figure 24 shows boxplots for each weight class with the 25th, 50th, and 75th percentile making up the main box, lines extending on either side within 1.5 times the interquartile range, and outliers shown as points beyond 1.5 times the interquartile range . Fuel burn tended to increase with heavier aircraft, along with the range of fuel burn values. Flight time was similar between weight classes due to the design of the simulation region of interest (i.e., the locations where aircraft initialized and deleted). Finally, total distance flown tended to increase with the aircraft weight class, although this was also affected by the design of the simulation region of interest.

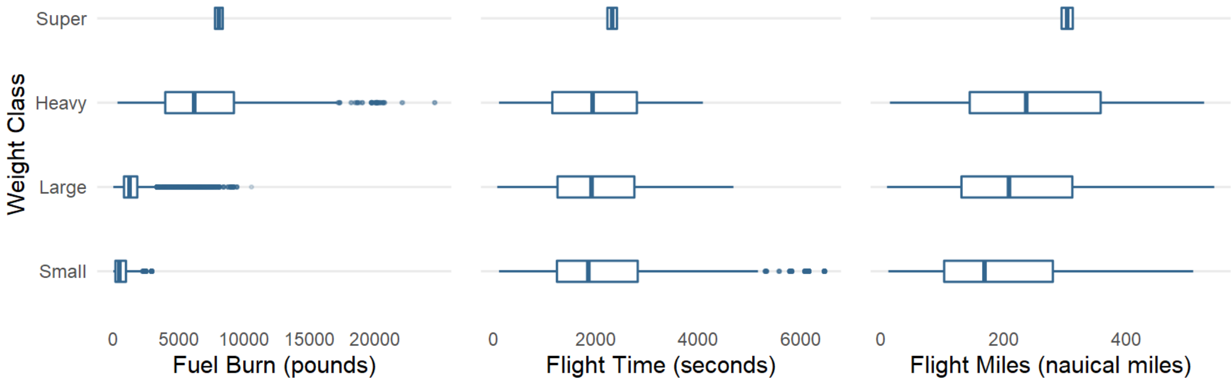

Figure 24: TBO Metric Boxplots by Aircraft Weight Class

The traffic type also affected the metrics. Background traffic, which featured more aircraft type models and tended to contain shorter flights through ZOB (e.g., flights that landed or took off within the simulation boundary), saw lower values compared to the traffic of interest, although both traffic types had equally large ranges of values, shown in Figure 25.

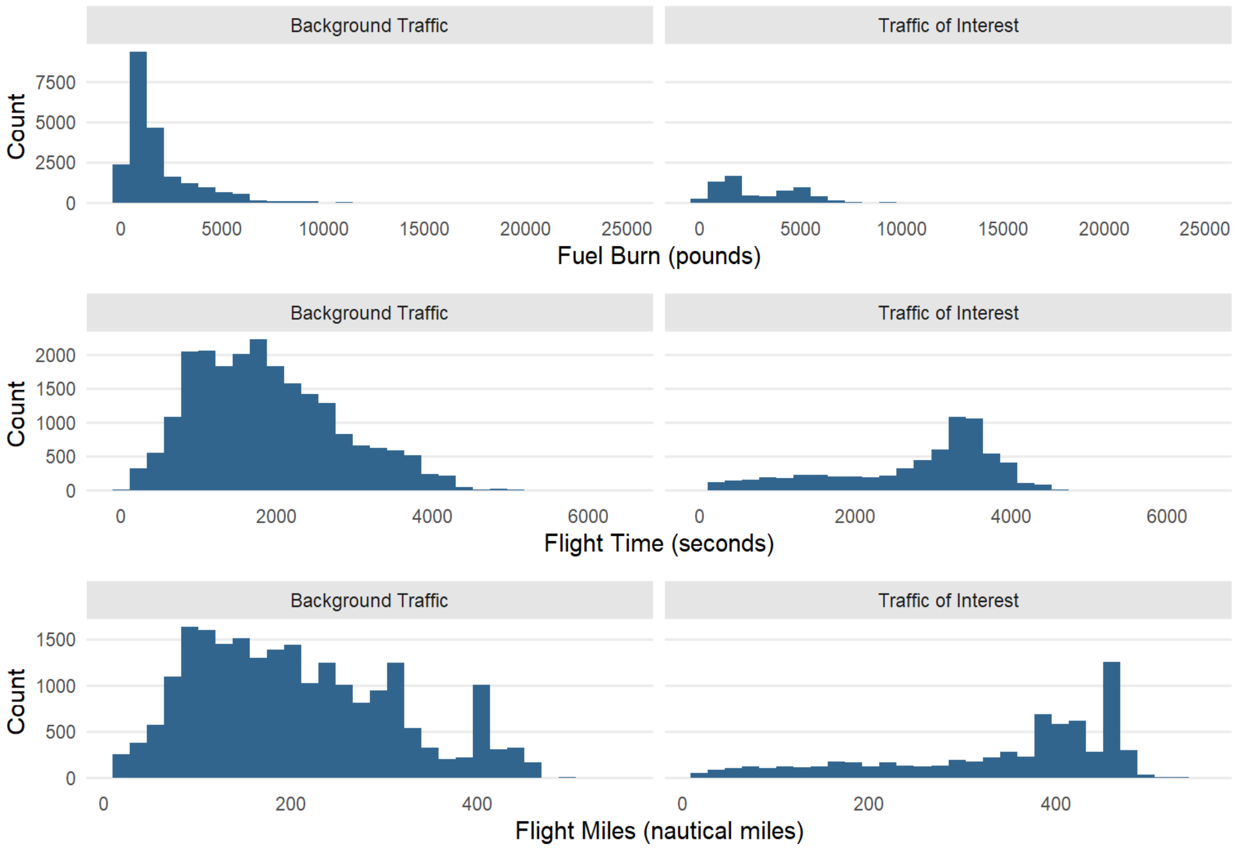

Figure 25: Fuel Burn, Flight Time, and Flight Miles for All TBO Scenarios by Traffic Type

One way to assess the variability from various sources is to model the metrics and create an analysis of variance table. Since the goal is to capture variability, the significance of terms in the models were not tested. A mixed-effects model was used on each metric, which were first standardized by subtracting the mean from each value and then dividing by the standard deviation. Mixed effect models are appropriate in situations when there are repeated measures, like the replicates in this case, and when the variable of interest is not normally distributed. The factors like the route type and traffic type were considered fixed effects since the levels would be the same if the experiment were repeated. The scenario, performance model, and unique call sign, which were nested within each scenario, were treated as random effects, because if the experiment were repeated, the researchers could choose a different traffic day and time, containing new flights with their own characteristics like performance model. The models for fuel burn, flight time, and flight miles used the following form, where the random effects are notated in parentheses:

$$\text{Metric} \sim \text{Route Type} + \text{Traffic Type} + (1 \mid \text{Scenario}) + (1 \mid \text{Performance Model}) + (1 \mid \text{CallSign:Scenario})$$

The modeling was done with the lme4 (v1.1-21, Bates, 2015) package in R. Table 12 shows the variance components for every random effect under each metric's model.

Table 12: Random Effect Variance Components by Metric

Random Effect	Standardized Fuel Burn		Standardized Flight Time		Standardized Flight Miles	
	Variance Component	Percent of Total	Variance Component	Percent of Total	Variance Component	Percent of Total
Scenario	0.00046	0.026%	0.00000	0.00%	0.00000	0.000%
Performance Model	1.42198	80.134%	0.04677	5.28%	0.06805	8.190%
CallSign:Scenario	0.35199	19.836%	0.83880	94.67%	0.76260	91.800%
Residual	0.00008	0.004%	0.00044	0.05%	0.00004	0.004%
Total	***1.77450***	***100.000%***	***0.88601***	***100.00%***	***0.83069***	***100.000%***

For standardized fuel burn, about 80% of the variance from random effects came from the performance model, with about 20% of the remaining variance coming from the unique call sign within the scenarios. Knowing the performance model helps understand the fuel burn values because aircraft type is very closely linked with fuel burn.

After accounting for the performance model and flight-to-flight variation, the scenario itself has nearly zero impact and the residual term, which represents the between-replicate variation, is very small. The residual variances across all three metrics was very small but not quite zero, meaning there is some variation replicate to replicate. The next section provides more details on that variation.

The models for standardized flight time and flight miles showed that the majority of the variability was flight-to-flight and only a small portion was attributed to the performance model unlike the fuel burn model. Flight time and miles flown were also different from the fuel burn model because the scenario components were zero, meaning that knowing the scenario gave no additional information. Because of the lack of variability between these scenarios, in future studies, fewer scenarios may be required and the results would be free from inconsistencies due to the unique scenario. The design of future studies may depend on the replicate-to-replicate variability as well.

5.3.2 Replicate Variability

The data validation process revealed a range of non-deterministic behavior seen between trajectories of the same flight over each replicate. While explicit simulation errors were removed from the data set, not all variation was closely examined due to the large number of flights. The following sections analyze the variation between replicates for fixed route and free route flights, each grouped by simulation source, either ASTOR or TMX, in order to pinpoint the causes of variability.

5.3.2.1 Fixed Route Variability

There were 5,869 fixed-routes in the TBO environment that had all three replicates intact. Because the routes were fixed, each replicate should have flown the exact same trajectory. The variance in fuel burn, flight time, and distance flown was calculated between the three replicates of each flight. Table 13 shows the average variances by source and Figure 26 shows the range of variances seen for each metric.

Table 13: Median Fixed-Route Replicate Standard Deviation by Metric and Source

Source	Median Fuel Burn Standard Deviation (pounds)	Median Flight Time Standard Deviation (seconds)	Median Distance Standard Deviation (nautical miles)	Number of Flights
ASTOR	0.11	0.000	0.004	2769
TMX	2.48	2.310	0.087	3100
Overall	***0.71***	***0.012***	***0.024***	***5869***

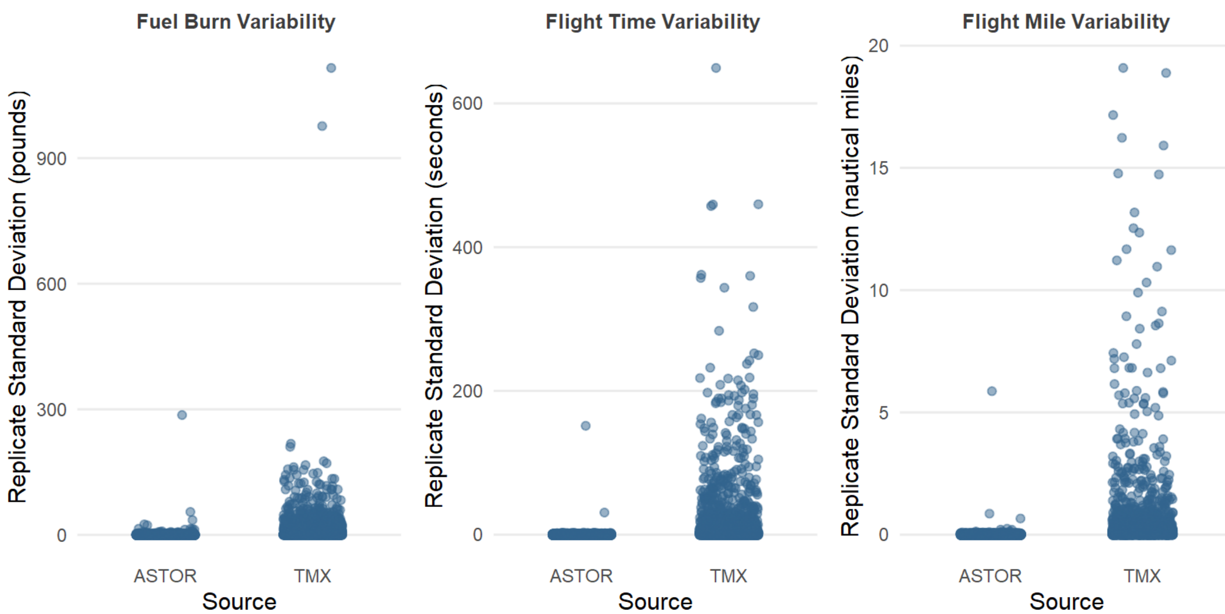

Figure 26: Within-Replicate Standard Deviation of Fuel Burn, Flight Time, and Flight Miles for Fixed Route TBO Scenario Flights by Simulation Source

TMX flights, all of which flew fixed routes, had more replicate-to-replicate variation than the fixed route ASTOR flights. The main reason for differences in TMX replicates was timing variation in data recording. Data recording ended at slightly different times along the flight, which lead to small differences in the cumulative fuel burned, flight miles flown, and by definition, the flight time.

5.3.2.2 Free Route Variability

Ideally, flights flying on free routes have the same trajectory when repeated; however, both AOP and the ATOS platform are non-deterministic. Section 5.3.2.1 showed that fixed-route ASTOR aircraft have a small variation replicate-to-replicate, so additional variation in the free-route ASTOR aircraft are likely to be attributed to the ATOS platform executing the route provided by AOP. There were 3,767 flights with all three replicates in the data set whose replicate variability is summarized in Table 14 and plotted in Figure 27. For most free routes, the standard deviation in fuel burn, flight time, and flight miles between the three TBO replicates is close to zero; however, the plot does show many positive values and some large outlying deviations between replicates. The values in Table 14 are very similar to the fixed-route ASTOR values in Table 13 from the previous section, meaning the same amount of variability occurs regardless of free-route vs. fixed route ASTOR flights.

Table 14: Median Free-Route Replicate Standard Deviation by Metric

Source	Median Fuel Burn Standard Deviation (pounds)	Median Flight Time Standard Deviation (seconds)	Median Flight Miles Standard Deviation (nautical miles)	Number of Flights
ASTOR	0.096	0	0.005	3767

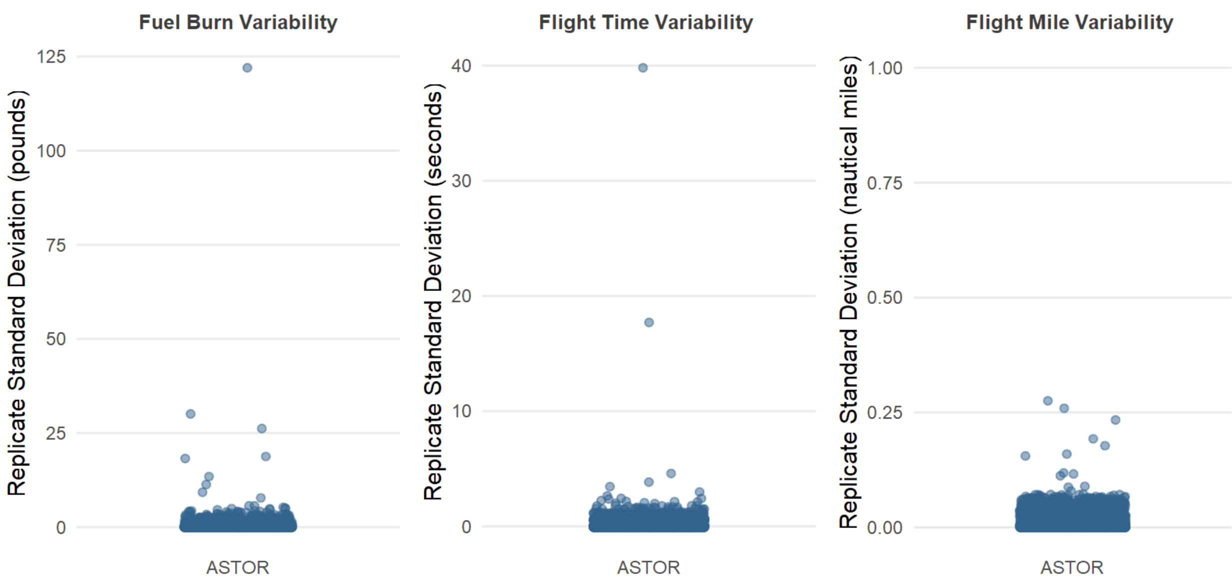

Figure 27: Replicate Standard Deviation of Fuel Burn, Flight Time, and Flight Miles for Free Route TBO Flights

5.3.3 Impact of Excluded Flights on Variability

Due to simulation errors, 3.8% of flights were removed from the initial data set containing all six scenarios. During data validation, certain flagged flights were rated by severity and placed into Subsets. Each progressive Subset after the first included all flights in the preceding Subset, and added previously excluded flights if they met specified criteria. Subset 1 contains all non-flagged flights, i.e., flights that successfully followed Data Comm maneuver instructions within specified error buffers, as well as flights identified as false positives during manual inspection. Subset 2 added any aircraft that appeared to properly execute Data Comm instructions before terminating at the simulation boundary to Subset 1. Subset 3 added flights that properly executed Data Comm maneuver instructions resulting from operational errors (e.g. step climb instructions received after the top of descent point along the route) to Subset 2. Subset 4 added flights that met the intent of a Data Comm maneuver but exhibited questionable or poor performance (e.g. multiple extreme, sudden changes in altitude in a short period). Adding flights in succession to separate data Subsets based on the selected criteria enabled the methodical removal of flights that could inadvertently skew results due to simulation and operational performance errors.

Repeating the previous analysis in Section 5.3.2.2 for each data Subset showed an increase in the number of flights with large standard deviations between TBO replicates. The number of outliers (standard deviation values more than three times the inter-quartile range) was calculated for each progressive data set. These values are shown in Table 15 along with the maximum standard deviation found per metric. As more flights with increasingly poor performance were included in the data, the number of standard deviation outliers increased and the maximum standard deviation values increased across all three metrics as well.

Table 15: Free-Route Standard Deviation Trends for TBO Scenario Replicates

Data Subset	Fuel Burn Standard Deviation		Flight Time Standard Deviation		Flight Miles Standard Deviation		Number of Flights
	Max (pounds)	Outlier Count	Max (seconds)	Outlier Count	Max (nautical miles)	Outlier Count	
Subset 1	122.10	212	39.84	764	0.28	82	3491
Subset 2	122.10	241	39.84	792	0.28	105	3767
Subset 3	122.10	244	142.32	829	13.13	104	3831
Subset 4	275.78	256	1034.75	876	88.80	95	3961

The inclusion of certain flights in the analyses would have also impacted their results and the understanding of the benefits of the TBO environment. Subset 2 was used for analysis of fuel burn and flight time differences between baseline and TBO flights, detailed in section 5.2, where free routes saw modest savings in fuel and time. When the same analytical methods were applied to Subsets 3 and 4, which included incremental additions of flights experiencing simulation errors, the median savings decreased due to the inclusion of poor-performing flights. Table 16 shows trends of several statistics for fuel burn and flight time differences for both traffic of interest and background traffic. The points on each trend line represent the results from Subsets 2, 3, and 4. Subset 1 was not analyzed because it excluded valid flights that were later identified as false positives (meaning they were incorrectly flagged as poor performing aircraft) during data validation. Hollow points on the trend lines represent negative values, solid points represent zero and positive values, and each trend line has a unique scale. For example, the median trend for differences in background traffic flight time savings progresses from -16 seconds in Subset 2 to -13 seconds in Subset 4, while the standard deviation pertaining to the same metric progresses from 88 to 114 seconds. For both metrics and traffic types, the median and maximum difference value either increased or stayed the same when changing the data Subset. The standard deviation of fuel burn and flight time differences increased overall, even though the sample size increased as well, which should automatically reduce variation. Overall, the process of data validation helped to reduce noise in the data from simulation and operational errors, and, as a result, the median fuel- and time-savings reported showed larger benefits that were also more precise.

Table 16: Benefit Metric Statistics across Data Subsets 2, 3, and 4

Difference Metric	Traffic Type	Median	Standard Deviation	Maximum	Number of Flights
	Subset	2 3 4	2 3 4	2 3 4	2 3 4
Fuel Burn	Traffic of Interest				
Fuel Burn	Background				
Flight Time	Traffic of Interest				
Flight Time	Background				

6. Future Development and Research Applications

A number of assumptions and limitations were imposed on the study described in this report. As such, further research and development may be conducted to increase the fidelity of the simulation environment to ensure that results are generalizable and accurate. This section describes future research and development that increases the fidelity of the simulation environment, as well as the application of the resulting TBO scenarios to future studies.

6.1 Increasing TBO Environment Scenario Fidelity

Although ZOB airspace was a suitable choice for this simulation use case, exploring and manipulating other factors related to airspace structure and traffic representation would increase scenario fidelity. Examples of these factors include utilizing as-filed company routes that include Standard Instrument Departure procedures and STARs instead of routes comprised of fixed waypoints in the simulation use case. Exploration of new airspaces instead of ZOB Class A airspace would provide a wider variety of data samples. The enhancement of simulation capabilities to support even higher traffic densities would enable a more accurate depiction of TBO environment traffic flows in a newly selected airspace. Additionally, while this simulation use case focused on a specific future timeframe, TBO environment scenarios can be adjusted to investigate situations involving select system capabilities within an environment that considers traffic projections for different timeframes as well. The impact of the COVID-19 global pandemic on air travel, for example, could delay the industry's recovery until at least 2024, which could affect the timeliness of a full TBO environment transition across airspace systems [41, 42].

Environmental factors included in the original simulation use case can be further enhanced to increase realism of scenarios in future research. Convective weather activity and high-resolution rapid refresh winds can be dynamically broadcast to aircraft in simulations. Conflict detection and resolution algorithms can be configured to consider convective weather cells in concert with route optimization calculations. In future studies that combine information from multiple resources in a future TBO environment, applying data fusion techniques to combine airborne and ground based convective weather data – such as what was done with the Airborne Weather Radar Processor prototype [19] – would potentially increase the precision of convective weather simulations.

Enhancements to multiple simulation capabilities could increase the reliability of baseline scenarios, as well as the flexibility and fidelity of all TBO scenarios. Increasing the number of available ASTOR performance model types would increase the number of available traffic of interest, as well as minimize model-to-aircraft type matching errors when choosing representative models. Including ATC modules that enables autonomous negotiation and approval between ground stations and aircraft could also enable future research that is more representative of future TBO. Incorporating TOA constraints to 4D trajectories as part of the baseline scenarios would also bring future studies a step closer to high-fidelity TBO environment investigations.

6.2 Application of TBO Environment Scenarios to Future Studies

The scenario development methodology presented in [17] and showcased in this report has profound effects on the ability of LaRC to conduct ATM research using realistic, high-density air traffic in its simulation scenarios. These scenarios can be used to conduct numerous types of research analyses, ranging from algorithmic performance studies using individual aircraft to fleet-scale benefit analyses.

For example, individual aircraft may be equipped with advanced airspace services to understand the algorithmic performance of a given service in the context of other aircraft and the ATM operation as a whole. Convective weather may be added to the simulation scenarios to evaluate the performance of an airspace service near convective weather. Fleets of aircraft (by aircraft type or by airline) may be equipped with one or more airspace services, and medium-high fidelity benefits analyses may be conducted to provide interested parties with information regarding the operational improvements that the airspace service may provide.

Furthermore, by using select aircraft equipped with one or more airspace services in a human-in-the-loop (HITL) mode, procedures and workload may be evaluated using operationally realistic scenarios. These scenarios allow flight crews and/or air traffic controllers to evaluate how the technology is used during operation, and may provide both quantitative and qualitative data regarding the airspace service.

Finally, by connecting the simulation capabilities used throughout this process with external simulations (a capability of ATOS discussed in Section 3.4.1), realistic integrated air-ground simulation activities may be conducted. This type of activity presents a unique opportunity to not only evaluate a given technology's performance or the procedures used to operate it, but to do so in a more realistic ATM operational environment, by including simulations or emulations of ground-based ATM technologies. Simulation activities like these provide a wealth of information regarding the expected operation once the technology matures to the point of an in-situ test (e.g., flight test) or an operational evaluation with a partner airline. Furthermore, connecting this simulation to a high-fidelity, motion-based cockpit simulator during a HITL experiment could expedite the maturation process toward operational flight tests in a futuristic environment with the addition of a human perspective, and could also support studies focusing on system-level operational evaluations.

7. Conclusions

This study provided an initial simulation of a futuristic TBO environment. This environment was defined by several assumptions regarding the operational paradigm for a 2040 TBO environment. These assumptions were applied to a simulation use case, and several simulation scenarios were evaluated in an exploratory study. The scenarios were generated using real-world SWIM data to define aircraft flight paths and traffic density, real-world environmental factors, and real-world operational constraints. The simulation use case enabled the validation of a strategic airborne trajectory management prototype. Use of a representative prototype within TBO scenarios that includes 4-D optimized trajectory planning with system-level constraints and user-preference capabilities could provide additional insights during future advanced trajectory management exploration activities.

An experiment design and data analysis approach was created to evaluate the benefits of this TBO environment, as well as scenario variability. Initial results from analyses indicate that application of a strategic airborne trajectory management prototype in a high traffic density simulation with Data Comm may potentially lead to flight benefits at varying impact levels. Flights in the TBO environment saved both fuel and time (p-value $< .001$), and the savings was driven by the free routes achieving benefits. Flights with free routes saw a median fuel savings of 17 pounds and median time savings of 7 seconds compared to baseline. However, TBO flights did not fly fewer flight miles; in fact, free routes flew farther than their baseline counterparts (p-value < 0.001, median difference of 0.1 nautical mile). The scenario variability analysis determined that no singular scenario was operationally or significantly different from the others. Therefore, these scenarios may be used in future experiments interchangeably without affecting data analyses.

The set of representative 2040 TBO environment scenarios generated as part of this study provide an adequate starting point for future studies in the airspace operations that would benefit from a realistic traffic environment. The documented scenario development methodology may also provide a roadmap for future studies that seek to generate scenarios with core TBO attributes as part of their baseline. Representation of forecasted high traffic density airspace in simulations was enabled by the use of the ATOS capability with compressed traffic, thereby increasing the realism of TBO environment research studies. Inclusion and use of multiple environmental factors, conflict detection and resolution algorithms, and additional airborne research support tools in future simulations, would expand the research space even further.

References

[1] W. N. Chan, B. E. Barmore, J. L. Kibler, P. U. Lee, C. J. O'Connor, K. Palopo, D. P. Thipphavong and S. J. Zelinski, "Overview of NASA'S Air Traffic Management-eXploration (ATM-X) Project," in *AIAA Aviation Technology, Integration, and Operations Conference*, Atlanta, GA, 2018.

[2] Federal Aviation Administration, "Data Communications," 25 06 2019. [Online]. Available: https://www.faa.gov/nextgen/how_nextgen_works/new_technology/data_comm/. [Accessed 08 10 2019].

[3] Federal Aviation Administration, "Advisory Circular 90-117," Washington, D.C., 2017.

[4] E. Hoffman, D. Ivanescu, C. Shaw and K. Zeghal, "Analysis of Constant Time Delay Airborne Spacing Between Aircraft of Mixed Types in Varying Wind Conditions," in *Fifth USA/Europe Air Traffic Management R&D Seminar*, Budapest, 2003.

[5] J. K. Klooster, A. Del Amo and P. Manzi, "Controlled Time-of-Arrival Flight Trials: Results and Analysis," in *Eighth USA/Europe Air Traffic Management Research and Development Seminar*, Napa, 2019.

[6] D. H. Williams and S. M. Green, "Airborne Four-Dimensional Flight Management in a Time-Based Air Traffic Control Environment," NASA/TM-4249, Hampton, 1991.

[7] NextGen Joint Planning and Development Office, "JPDO Trajectory-Based Operations (TBO) Study Team Report," JPDO, Washington, D.C., 2011.

[8] W. B. Cotton, R. Hilb, S. Koczo and D. J. Wing, "A Vision and Roadmap for Increasing User Autonomy in Flight Operations in the National Airspace," in *16th AIAA Aviation Technology, Integration, and Operations Conference*, Washington, D.C., 2016.

[9] D. J. Wing, "The TASAR Project: Launching Aviation on an Optimized Route Toward Aircraft Autonomy," NASA/TP–2019-220432, Hampton, 2019.

[10] M. C. Underwood, W. B. Cotton, C. E. Hubbs, M. J. Vincent, S. KC and D. J. Wing, "Intelligent User-Preferred Reroutes Using Digital Data Communication," NASA/TM-2020-5002126, Hampton, VA, 2020.

[11] M. C. Underwood, W. B. Cotton, C. E. Hubbs, M. J. Vincent, S. KC and D. A. Karr, "Incorporation of Time of Arrival Constraints in a Trajectory Optimization Technology," NASA/TM-2020-5005117, Hampton, 2020.

[12] W. B. Cotton, M. C. Underwood and C. E. Hubbs, "Strategic Airborne Trajectory Management," NASA/TM-2020-XXXXXXX, Hampton, 2020.

[13] Federal Aviation Administration, "FAA's NextGen Implementation Plan," US Department of Transportation, Washington, D.C., 2016.

[14] Federal Aviation Administration, "Time-Based Flow Management System Specification Document," U.S. Department Of Transportation, Washington, D.C., 2016.

[15] Federal Aviation Administration, "Aeronautical Information Manual," Federal Aviation Administration, Washington D.C., January 30, 2020.

[16] FAA, "FAA Aerospace Forecast: Fiscal Years 2019-2039," Federal Aviation Administration, Washington D.C., 2019.

[17] B. K. Buck, T. L. Barney, M. C. Underwood and R. C. Chartrand, "Design and Implementation of a Scenario Development Process for a 2040 Trajectory-Based Operations Simulation," NASA/TM-2020-5006526, Hampton, 2020.

[18] C. Alexander and et. al, "Rapid Refresh (RAP) and High Resolution Rapid Refresh (HRRR) Model Development," in *30th Conference on Weather Analysis and Forecasting (WAF)*, Boston, 2020.

[19] T. A. Lewis, K. A. Burke, M. C. Underwood and D. J. Wing, "Weather Design Considerations for the TASAR Traffic Aware Planner," in *19th AIAA Aviation Technology, Integration, and Operations Conference*, Dallas, 2019.

[20] Federal Aviation Administration, "FAA Order JO 4700.10B, Special Use Airspace," Federal Aviation Administration, Washington D.C., February 16, 2020.

[21] Federal Aviation Administration, "Special Use Airspace & Air Traffic Controlled Assigned Airspace," [Online]. Available: http://sua.faa.gov.

[22] Langley Enhanced IT Services (LITES), "Airspace and Traffic Operations Simulation (ATOS) System Software Project: ATOS System Capabilities Document, Version 5.0," NASA Langley Research Center, Hampton, VA, October 31, 2015.

[23] D. Finkelsztein, T. Lung, R. A. Vivona, J. Bunnell, D. Mielke and W. Chung, "Airspace and Traffic Operations Simulaiton for Distributed ATM Research and Development," in *AIAA*, 2005.

[24] F. J. L. Bussink, J. Hoekstra and B. Heesbeen, "Traffic Manager: A Flexible Desktop Simulation Tool Enabling Future ATM Research," in *24th Digital Avionics Systems Conference*, Washington D.C., 2005.

[25] B. Heesbeen, H. Jacco and M. Valenti Clari, "AIAA 2003-5368, Traffic Manager: Traffic Simulation for Validation of Future ATM Concepts," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Austin, TX, August 2003.

[26] R. C. Chartrand and K. M. Ballard, "AIAA 2017-3599, Benefits of using pairwise trajectory management in the Central East Pacific," in *AIAA Aviation 2017 Conference*, Denver, CO, June 2017.

[27] F. J. L. Bussink, N. A. Doble, B. E. Barmore and S. Singer, "A Fast-Time Simulation Environment for Airborne Merging and Spacing Research," in *23rd Digital Avionics Systems Conference*, Salt Lake City, UT, October 2004.

[28] T. L. Barney, M. C. Underwood and B. K. Buck, "Simulation and Flight Testing Environments for the TASAR Traffic Aware Planner," in *19th AIAA Aviation Technology, Integration, and Operations Conference*, Dallas, 2019.

[29] M. T. Palmer and M. G. Ballin, "A High-Performance Simulated On-Board Avionics Architecture to Support Traffic Operations Research," in *AIAA Modeling and Simulation Technologies Conference*, Austin, 2003.

[30] P. C. Glaab and M. M. Madden, "Benefits of a Unified LaSRS++ Simulation for NAS-Wide and High-Fidelity Modeling," in *33rd Digital Avionics Systems Conference*, Colorado Spring, CO, October 2014.

[31] R. Barhydt, M. T. Palmer and T. M. Eischeid, "Development and Evaluation of an Airborne Separation Assurance System for Autonomous Aircraft Operations," in *24th Congress International Council of the Aeronautical Sciences*, Yokohama, 2004.

[32] D.-J. Liu and W. W. Chung, "AIAA 2004-5259, ASTOR: An Avionics Concept Test Bed in a Distributed Networked Synthetic Airsapce Environment," in *AIAA Modeling and Simulation Technologies Conference and Exhibit*, Providence, RI, August 2004.

[33] D. Karr, R. Vivona, D. Roscoe, S. DePascale and D. Wing, "Autonomous Operations Planner: A Flexible Platform for Research in Flight-Deck Support for Airborne Self-Separation," in *AIAA-2012-5417*, Washington, DC, 2012.

[34] B. E. Barmore, E. Johnson, D. J. Wing and R. Barhydt, "Airborne Conflict Management within Confined Airspace in a Piloted Simulation of DAG-TM Autonomous Aircraft Operations," in *5th US/Europe Air Traffic Management Research and Development Seminar*, Budapest, 2003.

[35] D. J. Wing, T. Prevot, J. L. Murdoch, C. D. Cabrall, J. R. Homola, L. H. Martin, J. S. Mercer, S. T. Hoadley, S. R. Wilson and C. E. Hubbs, "Comparison of Ground-Based and Airborne Function Allocation Concepts for NextGen Using Human-In-The-Loop Simulations," in *10th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Fort Worth, 2010.

[36] D. J. Wing, J. L. Murdoch, J. P. Chamberlain, M. C. Consiglio, S. T. Hoadley, C. E. Hubbs and M. T. Palmer, "Functional Allocation with Airborne Self-Separation Evaluated in a Piloted Simulation," in *27th Congress of the International Council of the Aeronautical Sciences (ICAS)*, Nice, 2010.

[37] D. J. Wing, R. Bardhydt, B. E. Barmore and K. Krishnamurthy, "Pilot Interactions in an Over-Constrained Conflict Scenario as Studied in a Piloted Simulation of Autonomous Aircraft Operations," in *5th US/Europe Air Traffic Management Research and Development Seminar*, Budapest, Hungary, 2003.

[38] R. Barhydt, P. Kopardekar, V. Battiste, N. Doble, W. Johnson, P. Lee, T. Prevot and N. Smith, "Joint NASA Ames/Langley Experimental Evaluation of Integrated Air/Ground Operations for En Route Free Maneuvering," in *6th USA/Europe Seminar on Air Traffic Management Research and Development*, Baltimore, 2005.

[39] K. A. Burke, D. J. Wing and T. A. Lewis, "Pilot Subjective Assessments During an Investigation of Separation Function Allocation Using a Human-In-The-Loop Simulation," in *AIAA Aviation Technology, Integration, and Operations (ATIO) Conference*, Los Angeles, 2013.

[40] Federal Aviation Administration, "Aircraft Type Designators, Effective Date 09/17/2019," FAA Order JO 7360.1E, Washington, D.C..

[41] International Air Transportation Association, "IATA Pressroom," IATA, 28 July 2020. [Online]. Available: https://www.iata.org/en/pressroom/pr/2020-07-28-02/. [Accessed 3 August 2020].

[42] D. McHugh, "Air Travel Expected To Not Recover Before 2024," ABC, 28 July 2020. [Online]. Available: https://abcnews.go.com/Business/wireStory/air-travel-expected-recover-2024-72030237. [Accessed 3 August 2020].

Appendix A. Detailed Results

Benefits of TBO

The contents in this appendix include additional details from the results discussed in section 5, including total flight counts across all six scenarios, and distributions of fuel burn, flight time, and flight mile differences between background and traffic of interest.

Table A1 provides the final flight counts used in the analysis, as discussed in section 5.1. Flight counts are listed for each scenario, replicate, and flight type. Scenarios 4 and 9 were the most populous.

Table A1: Flight Count by Flight Type, per Run.

Run			Flight Type						Total Flights
Scenario	Airspace	Replicate	BCR	BNX	BCX	TCR	TNX	TCX	
2	Baseline	0	0	353	828	0	76	235	*1492*
2	TBO	1	440	353	387	173	76	62	*1491*
2	TBO	2	441	353	387	172	76	62	*1491*
2	TBO	3	441	353	387	173	76	62	*1492*
3	Baseline	0	0	384	792	0	111	259	*1546*
3	TBO	1	425	384	367	183	111	76	*1546*
3	TBO	2	424	384	367	183	111	76	*1545*
3	TBO	3	425	384	367	183	111	76	*1546*
4	Baseline	0	0	433	894	0	155	284	*1766*
4	TBO	1	475	433	418	207	155	77	*1765*
4	TBO	2	476	433	418	207	155	77	*1766*
4	TBO	3	475	433	418	207	155	77	*1765*
7	Baseline	0	0	354	825	0	83	241	*1503*
7	TBO	1	442	354	382	176	83	65	*1502*
7	TBO	2	441	354	382	175	83	65	*1500*
7	TBO	3	442	354	382	175	83	65	*1501*
8	Baseline	0	0	390	798	0	107	268	*1563*
8	TBO	1	436	390	361	174	107	94	*1562*
8	TBO	2	436	390	361	174	107	94	*1562*
8	TBO	3	435	390	361	174	107	94	*1561*
9	Baseline	0	0	503	824	0	151	305	*1783*
9	TBO	1	444	503	379	204	151	101	*1782*
9	TBO	2	444	503	379	203	151	101	*1781*
9	TBO	3	443	503	379	204	151	101	*1781*
Total			***7985***	***9668***	***11843***	***3347***	***2732***	***3017***	***38592***

Section 5.2.1 discussed the fuel burn benefits seen in TBO runs. Figure A1 shows the distribution of fuel burn differences for all flights and scenarios, separated along the intersection of route type and traffic type, with the marginal distributions on the perimeter. Flights on fixed routes and those considered background traffic show no fuel savings a majority of the time while there is more spread of both fuel savings and increased fuel usage among free routes and traffic of interest.

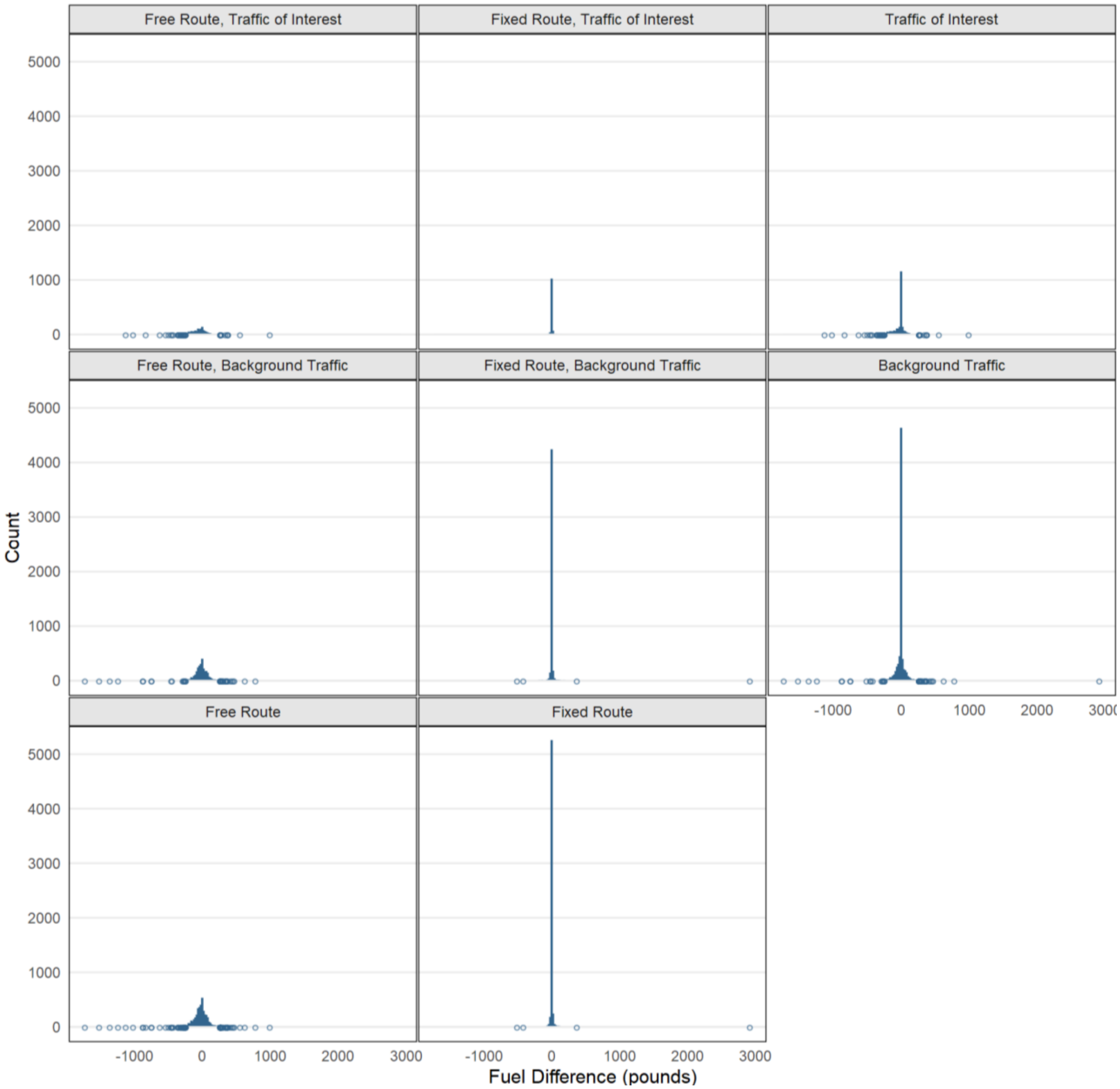

Figure A1: Fuel Burn Difference by Route Type and Traffic Type

Figure A2 shows the distribution of flight time differences for all flights and scenarios, separated by route type in the first two columns and traffic type in the first two rows. Table 8 from section 5.2.2 details the statistics from these distributions. The vast majority of flights that were considered background traffic saw no time savings while free routes, especially those considered traffic of interest, saw small time savings.

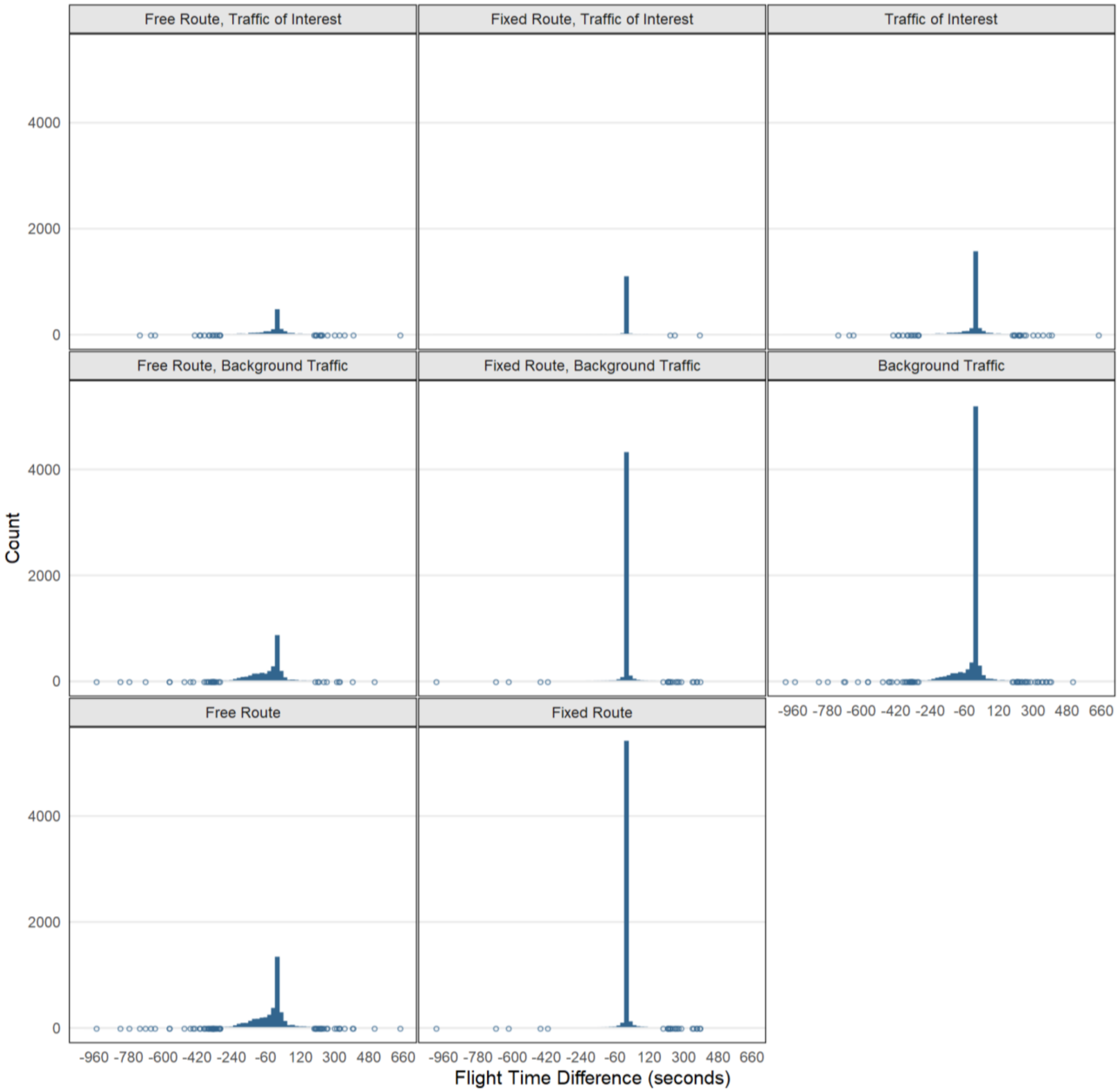

Figure A2: Flight Time Difference by Route Type and Traffic Type

Flight mile differences are discussed in section 5.2.3. Figure A3 shows the distribution of flight mile differences for all flights and scenarios, separated by route type and traffic type. There was no difference in nautical miles flown between baseline and TBO runs for most of the fixed route flights, as well as the background traffic. Free route flights that were also traffic of interest saw a small increase in distance traveled compared to other flights.

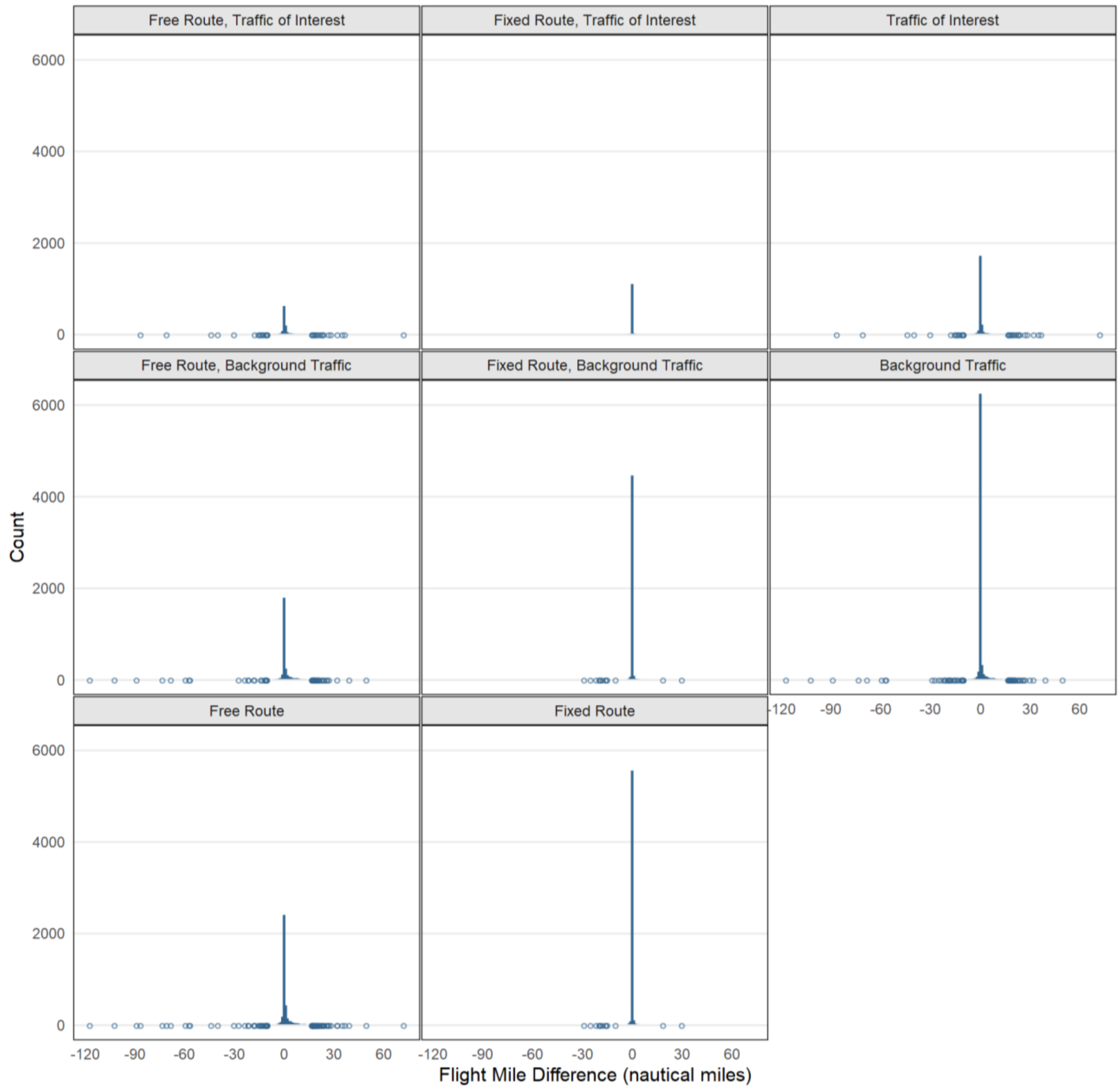

Figure A3: Flight Miles Difference by Route Type and Traffic Type

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-11-2020

2. REPORT TYPE
Technical Memorandum

3. DATES COVERED *(From - To)*
Oct 2019 - Sep 2020

4. TITLE AND SUBTITLE
Simulation of a Representative Future Trajectory-Based Operations Environment

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Barney, Terique L.; Ballard, Kathryn M.; Buck, Bill K.; Underwood, Matthew C.; Chartrand, Ryan C.

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
629660.02.40.07.01.02

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NASA Langley Research Center
Hampton, Virginia 23681-2199

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546-0001

10. SPONSOR/MONITOR'S ACRONYM(S)
NASA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NASA-TM-20205006885

12. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified
Subject Category
Availability: NASA STI Program (757) 864-9658

13. SUPPLEMENTARY NOTES

14. ABSTRACT
Trajectory-Based Operations focuses on modernizing the current operating paradigm to increase efficiency, predictability, resilience, and flexibility while migrating toward greater operational autonomy across the airspace. This report describes characteristics and assumptions applied to a scenario development methodology to study a representative 2040 Trajectory-Based Operations environment in a simulation use case. Also included are descriptions of the study design and analysis approach, discussion of the simulation results, and application of these scenarios to future research activities.

15. SUBJECT TERMS
Trajectory-Based Operations, TBO, Simulation, Airborne Trajectory Management, ATM, Simulation Use Case,TBO Benefits, Scenario Development, ASTOR, ATOS, TMX, AOP, Air Transport Operations Research

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			STI Help Desk (email: help@sti.nasa.gov)
					19b. TELEPHONE NUMBER *(Include area code)*
				56	(757) 864-9658