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Effects of Future Space Vehicle Operations on a Single Day in the National Airspace System: A Fast-Time Computer Simulation

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April 2015

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U.S. Department of Transportation
Federal Aviation Administration

William J. Hughes Technical Center
Atlantic City International Airport, NJ 08405

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16. Abstract

This document describes the objectives, methods, analyses, and results of a study used to quantify the effects of future space operations on the National Airspace System (NAS), and to demonstrate the possible benefits of one proposed strategy to minimize these impacts. The Federal Aviation Administration's (FAA) Concept Analysis Branch used fast-time computer simulation to identify changes to flight delay, flight distance, fuel burn, and sector throughput caused by increased space vehicle (SV) operations forecasted for 2018 and 2025. Researchers then collaborated with Stanford University to run additional scenarios demonstrating the potential benefits of using dynamic airspace closures designed by the university's Aerospace Design Lab. Results will be used to support the Space Vehicle Operations (SVO) program in defining the problem statement and requirements for procedural and automation changes in the Next Generation Air Transportation System (NextGen).

Two sets of fast-time simulation scenarios were run to quantify changes in NAS efficiency and capacity metrics. The first set of scenarios simulated future traffic and SV operations using current air traffic control procedures, while the second set of scenarios simulated a proposed procedural change using Stanford's 4D Compact Envelopes. Each set of simulated scenarios varied two factors: forecasted traffic year and level of SV operations. NAS traffic levels forecasted for 2018 and 2025 in the Terminal Area Forecast (TAF) were simulated to capture changes in NAS performance with increased amounts of traffic. Researchers from the FAA's Concept Analysis Branch and Stanford University worked with the SVO program lead to define three levels of SV operations in 2018 and 2025 based on predictions made by the FAA's Office of Commercial Space Transportation. SV operation levels of low, medium and high were simulated for each forecasted traffic year; this variability was included to account for the uncertainty of the commercial space industry's future success and demand.

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Executive Summary

With the introduction of commercial space operators, space vehicle operations are expected to greatly increase in the coming years. Every launch and reentry in the United States requires the space vehicle (SV) to pass through the National Airspace System (NAS), resulting in the implementation of special activity airspace(s) (SAA). While this is done to protect aircraft during the SV operation, the airspace closures impede the flow of air traffic. The Federal Aviation Administration (FAA) is conducting research to evaluate the potential effects of future commercial space operations and explore the benefits of proposed mitigation strategies.

In this study, the FAA's Concept Analysis Branch (ANG-C41) quantified the potential effects of future space launch and reentry operations on En Route NAS operations when today's typical airspace closures are used. ANG-C41 researchers also worked with Stanford University to test the possible benefits of using a new method to close airspace during SV operations while minimizing effects on the NAS. Stanford's four-dimensional (4D) compact envelopes were used in this study to demonstrate one mitigation strategy for potential NAS effects.

Three sets of fast-time computer simulations were conducted to simulate six potential days of SV operations in the NAS for the forecast years 2018 and 2025. One set of simulation scenarios modeled the NAS with no SV operations; a second set represented the NAS when air traffic was protected from SV operations using airspace closures typically used today; and a third set modeled the use of Stanford University's 4D compact envelopes in place of today's restricted airspaces and hazard areas. Changes to En Route NAS operations due to SV launches and reentries were measured through flight efficiency (flight distance, fuel burn, and flight duration) and sector occupancy metrics.

Flights that were directly affected by the airspace closures experienced statistically significant changes on all six simulation days, although the change in flight distance, fuel burned, and flight duration varied for each day modeled. Flights that rerouted around closed airspace flew on average an additional 3.5 to 18.7 nautical miles (NM), burned between 43.1 and 200.4 pounds (lbs) more fuel, and flew between 0.4 and 2.6 minutes (min) longer. Additionally, the number of times a sector violated their aircraft count threshold was affected by the introduction of SV operations. It was concluded that this change in sector throughput would result in additional air traffic management actions to safely manage air traffic around the SV operations; controller workload would likely increase due to the coordination required to implement these maneuvers and maintain staffing levels.

When Stanford University's 4D Compact Envelopes were used to protect air traffic during SV operations, rerouted flights experienced statistically significant savings. Flights rerouted around the 4D compact envelopes on all six simulation days saved on average 3.5 to 18.7 NM flight distance, between 43.1 and 200.3 lbs of fuel, and 0.4 to 2.6 min of flight time compared to the current procedures. The use of 4D compact envelopes also negated the effect on sector throughput that was observed in the previous analysis where current airspace closures were used to protect air traffic during SV operations. This may indicate a benefit to controller workload; however, other air traffic management actions required to implement 4D compact envelopes were not simulated. A follow-on study including a Human-in-the-Loop experiment was recommended to further examine impacts to controller workload.

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1 Introduction

President Lyndon B. Johnson once said, “if I could get one message to you it would be this: the future of this country and the welfare of the free world depends upon our success in space. There is no room in this country for any but a fully cooperative, urgently motivated all-out effort toward space leadership. No one person, no one company, no one government agency, has a monopoly on the competence, the missions, or the requirements for the space program (NASA, 2000).” While this was said many years ago, its spirit is more alive today than it ever has been. With the introduction of commercial space operators, space vehicle operations are expected to greatly increase in the coming years (FAA, 2013). Each launch and reentry in the United States requires the vehicle to pass through the National Airspace System (NAS), resulting in the implementation of special activity airspace(s) (SAA). While this is done to protect aircraft during space vehicle (SV) operations, the airspace closures impede the flow of air traffic. The Federal Aviation Administration (FAA) is conducting research to evaluate the potential effect of future commercial space operations and explore the benefits of proposed mitigation strategies.

1.1 *Purpose*

This study aimed to quantify the effects of future space operations on a single day of En Route operations in the NAS and to demonstrate the possible benefits of one proposed strategy to minimize these impacts. The FAA’s Concept Analysis Branch (ANG-C41) used fast-time computer simulation to identify changes to flight distance, fuel burn, flight duration and sector throughput caused by increased SV operations forecasted for 2018 and 2025. Researchers collaborated with Stanford University to demonstrate the potential benefits of using dynamic airspace closures designed by the university’s Aerospace Design Lab. Results will be used to support the Space Vehicle Operations (SVO) program in defining the problem statement and requirements for procedural and automation changes in the Next Generation Air Transportation System (NextGen).

The following research questions were answered through this study:

1. *Using current Air Traffic Control (ATC) tools, procedures, and processes, how will the potential increase in SV operations affect En Route traffic in the future?*

2. *Is it possible to minimize the potential effects of SV operations on the NAS by utilizing new airspace closure procedures such as Stanford University’s 4D Compact Envelopes concept? If so, what are the potential benefits associated with this change?*

1.2 *Background*

Over the past century in the United States, space operations have typically been planned, organized, and executed by government entities. With the recent decommissioning of the National Aeronautics and Space Administration’s (NASA) Space Shuttle program and the research and development of commercial space operations, new innovations are rapidly ushering in an unprecedented era of space operations and making it accessible to more people. As a result, SV operations are expected to greatly increase in the coming years across the NAS (FAA, 2013). Figure 1 illustrates current and future launch sites in the United States. Each launch and reentry requires the vehicle to pass through the NAS, which currently requires the implementation of special activity airspace(s) (SAA) to protect aircraft from off-nominal events during SV operations.

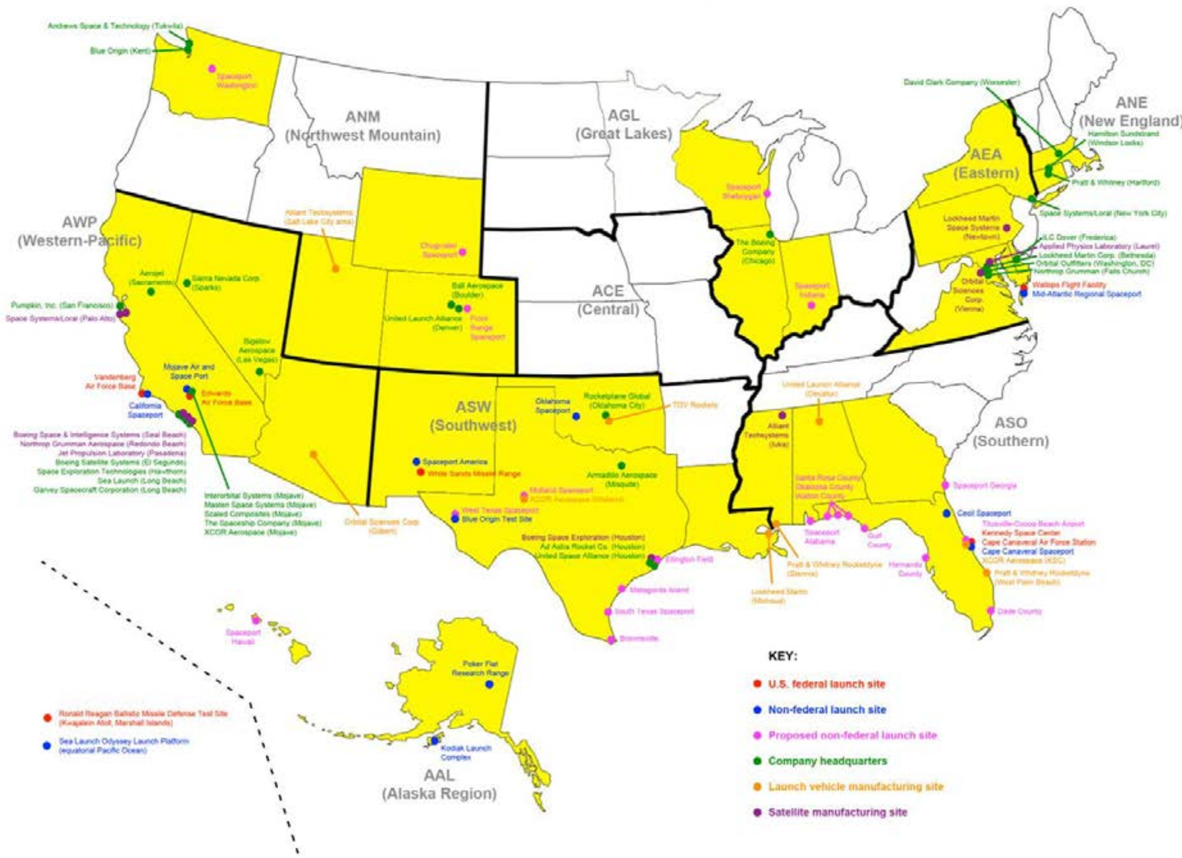

Figure 1. Current and Future Locations of Space Operations (Hatton, 2013)

Historically, SV operations have been infrequent, isolated events that were primarily initiated by NASA, the Department of Defense, or a collaboration of the two. To ensure the safety of other NAS users (i.e. airline, general aviation, etc.) during a launch or reentry operation, these organizations coordinated with the affected FAA Air Traffic Management (ATM) team to block and manage airspace that could be impacted by the SV operation. This coordination was executed through a combination of Notices to Airmen (NOTAMs) and Air Traffic Control System Command Center Advisories (Hayes, 2008).

Today's procedures for managing NAS traffic during SV operations significantly affect the efficiency of flights in the area surrounding each launch or reentry. An analysis of the SpaceX Falcon 9 launch from Cape Canaveral on March 1, 2013 showed that the SV operation caused impacted flights in the Florida centers to travel up to 84 Nautical Miles (NM) longer, to burn up to 2,387 more pounds (lbs) of fuel, and to fly as much as 23 minutes (min) longer (Young and Kee, 2014). As the number of spaceflight operations increase over the next decade, the existing procedures and processes for managing and coordinating spaceflight operations will not be able to efficiently accommodate this expansion of the NAS environment. Consequently, different architectures, tools, procedures, and processes must be developed in order to minimize the effects of space operation on the NAS while maintaining the safety of every user.

1.3 *Document Organization*

The remainder of this document provides details on the methodology used to conduct this study, the results of the analysis, a summary of the study's conclusions and recommendations for next steps.

Section 2 provides detailed information on the study metrics and analysis design. The scope of the study is defined and a list of tools and data utilized in the study is provided. The simulation scenarios are defined and analysis assumptions and limitations are acknowledged in this section as well. The analytical methods and results are included in Section 3, and a summary of conclusions drawn from the analyses and recommendations for future work are discussed in Section 4. Appendix A includes a list of the NOTAMs used to form assumptions on current day procedures for closing airspace surrounding SV operations, and Appendix B contains a detailed table containing descriptions of the SV operations assumed for the study along with corresponding screenshots from the simulation model of the airspace closures used in each scenario. Appendix C includes a summary count of the interactions between flights and airspace closures in each scenario, and Appendix D contains a detailed summary of the sector occupancy analysis results.

2 Study Methodology

This study focused on understanding the potential effects of increased SV operations in the future and demonstrating the benefits of using new strategies to minimize these effects. To answer the two research questions listed in Section 1.1, three sets of fast-time simulation scenarios were run to quantify changes in flight efficiency and capacity metrics. The first set of scenarios simulated future air traffic with no SV operations and served as a baseline for comparisons. In the second set of scenarios, six days of SV operations with various locations and vehicles were represented in the simulation by the airspace closures they typically cause today. Finally, the third set of scenarios simulated the same SV operations through the use of Stanford University's proposed 4D compact envelopes.

For each set of simulation scenarios, two factors were used: forecasted year and level of SV operations. Traffic levels forecasted for 2018 and 2025 in the Terminal Area Forecast (TAF) were simulated to capture changes in NAS performance with increased amounts of traffic. Researchers from the FAA's Concept Analysis Branch and Stanford University worked with the SVO program lead to define three levels of SV operations in 2018 and 2025 based on predictions made by the FAA's Office of Commercial Space Transportation (AST). Low, medium and high levels of SV operations in 2018 and 2025 were simulated as six separate days with different locations and space vehicles. This variability was included to account for the uncertainty of the commercial space industry's future success and demand.

The simulation scenarios and their associated comparisons are shown in Figure 2. To answer the first research question, scenarios representing increased SV operations in 2018 and 2025 with today's typical airspace closures were compared against baseline scenarios with no SV operations in the same years. This comparison allowed identification of changes to flight efficiency and sector occupancy caused by the introduction of commercial SV operations. Then, as the figure illustrates, the same scenarios simulating SV operations in the NAS using current airspace restrictions were compared against scenarios where Stanford University's 4D compact envelopes were used to estimate benefits associated with the proposed mitigation strategy.

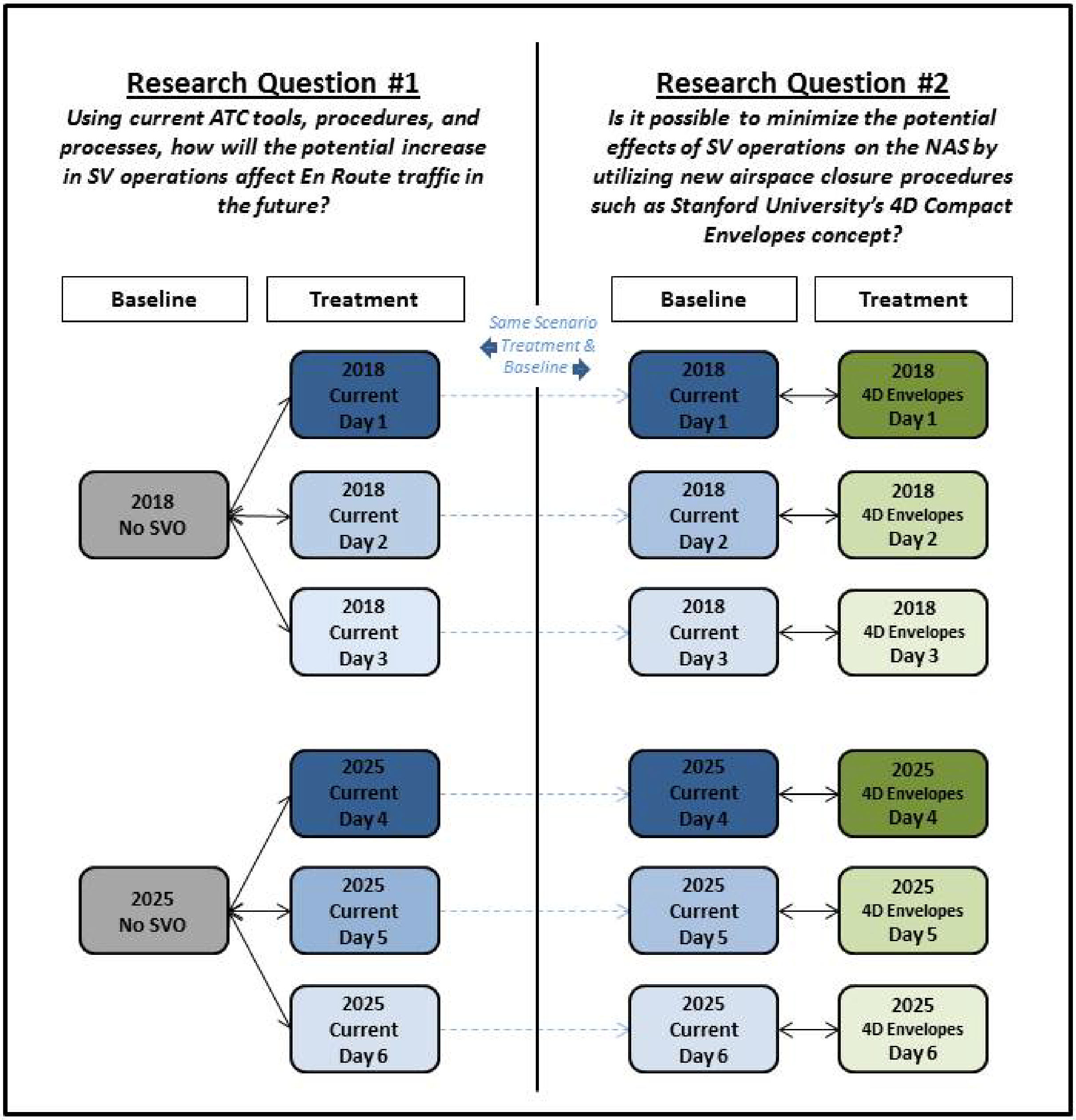

Figure 2. Simulation Scenarios for Research Questions 1 and 2

2.1 ***Metric Selection***

The following metrics were used to quantify changes to NAS efficiency and sector occupancy in this simulation study.

- Total Flight Duration
  This metric represents the total time a flight flew in the NAS. It is used to quantify added flight delays or time savings for an individual flight.

- Total Fuel Burned
  This metric represents the total amount of fuel used during the flight while in the NAS. It is used to quantify the additional amount of fuel burned or saved by an individual flight.

- Total Distance Flown
  This metric represents the total distance of the flight in the NAS. It is used to quantify the additional distance flown or saved by an individual flight.

- Sector Occupancy
  This metric is the number of aircraft that passed through a sector in a 15 minute period. Sector occupancy is commonly used to identify potential controller workload problems. It can be compared against each sector's Monitor Alert Parameter (MAP) value. MAP values represent a threshold standard for manageable sector occupancy, although it should be noted that they are theoretical in nature. MAP values for this study were obtained from the Performance Data Analysis and Reporting System (PDARS) (ATAC, 2010). MAP threshold violations may indicate the potential for higher workload that would result from managing the sector airspace to meet the MAP value.

2.2 ***Analysis Design***

This section provides a brief description of the study's analysis methodology including the models and tools used, a detailed description of the factors considered in the experiment, simulation scenario definitions and a listing of the assumptions and limitations of the study.

2.2.1 Models and Tools

ANG-C41 has a number of fast-time simulation models and analysis tools to assess the benefits of proposed concepts. The following tools were chosen for this analysis based on the individual study questions.

2.2.1.1 AirTOp Fast-Time Simulation Model

AirTOp is a commercial off-the-shelf, multi-agent simulation tool developed by Airtopsoft SA, a European company specializing in the development of air traffic simulation and optimization systems (AirTOpsoft, 2007). The AirTOp simulation tool is designed to capture many aspects of the ATM domain. AirTOp can model controller roles, tasks and workload for radar controllers, planning controllers and airport controllers. The tool includes a user defined rule-based system to simulate en-route restrictions, re-routing, approach and departure sequencing, and runway dependencies. For this study, AirTOp was the fast-time simulation tool used to conduct a macroscopic study to quantify the potential effects of future SV operations on the NAS.

2.2.1.2 JMP® Statistical Software

The statistical software product JMP® was used to analyze the simulation output and compare the effects of SV operations on the NAS. JMP is a product of the SAS Institute that provides a user-friendly graphical interface to perform both descriptive and inferential statistical analyses and allows the user to easily manipulate data tables and create graphical representations of data.

2.2.2 Scope

The scope of this study is defined in the subsections below. While the simulations were considered NAS-wide since flights and SV operations across the United States were modeled, only En Route operations were simulated. No changes to arrival and departure procedures, airport ground operations, or secondary impacts of rerouted flights were represented in this study; thus, no conclusions could be made on the overall effect of SV operations on the NAS. Follow-on research was recommended to evaluate the impact of SV operations on other domains of the NAS.

2.2.2.1 Airport

Since this was a NAS-wide study, airports located in the Continental United States (CONUS) and in Hawaii and Alaska were included in all simulation scenarios. However, all airports were modeled only as the origin and destination point of flights. No arrival and departure procedures or ground operations were simulated.

2.2.2.2 Airspace

The airspace modeled for this fast-time study consisted of the 20 CONUS En Route Air Route Traffic Control Centers (ARTCCs), Honolulu Control Facility (ZHN), Anchorage En Route ARTCC (ZAN), and their associated sub-sectors. The CONUS ARTCC data for this simulation was obtained from the NAS Adaptation Services Environment (NASE) web database. The NASE web product was developed by the FAA to provide access to NAS adaptation resources recorded from the NAS Host and/or En Route Automation Modernization (ERAM) Systems. The ZHN and ZAN airspace information was obtained from the Traffic Flow Management System (TFMS) database.

2.2.2.3 Weather

No weather data was modeled or considered in this study. It was assumed that no weather event was present in the NAS on the simulated days which allowed researchers to isolate the effects of space vehicle operations.

2.2.2.4 Air Traffic

The CONUS flights simulated in this study were obtained from forecast schedules developed by the FAA's Forecast Analysis group (AJR-G1). This traffic was based on recorded, operational traffic data from May 4, 2013 and increased to match forecasted levels for 2018 and 2025 as predicted in the TAF (Cheng, Gulding, Baszczewski, & Galaviz, 2011). The two forecast years, 2018 and 2025, are known to be the mid-term and far-term implementation dates for the Next Generation Air Transportation System (NextGen). The number of flights included in the schedules was constrained by today's airport capacities to ensure a realistic traffic demand. The selected sample of recorded traffic data was a clear weather day, allowing researchers to assume that the planned routes were unconstrained by convective weather.

In addition to the CONUS traffic, flights within ZHN and ZAN were also included to capture effects on local traffic surrounding SV operations at Spaceport Hawaii in Honolulu as well as spaceports in Poker Flat and Kodiak, Alaska. Local air traffic in these areas was not included in the forecasted CONUS schedules; therefore, ANG-C41 requested and obtained historical flight plan information for two heavy traffic days through the System Manager of the FAA Air Traffic Organization's Micro-En Route Automated Radar Tracking System (Micro-EARTS). ZAN provided flight plan information for July 26 and 27 of 2014, and ZHN supplied the same information for August 15 and 16 of 2014. This data was parsed and merged with the forecasted traffic to form a complete set of flights in the United States.

The 2018 and 2025 forecast traffic schedules were combined with the data from ZHN and ZAN to create a 2018 and 2025 air traffic schedule. The 2018 schedule was used for all 2018 simulation scenarios, and the 2025 schedule was used for all 2025 scenarios. It is important to note that the 2018 air traffic schedule was not a subset of the 2025 schedule; the 2018 and 2025 forecast schedules were created with separate, distinct processes. Therefore, a pair-wise flight comparison was not made between the 2018 and 2025 scenarios.

2.2.2.5 SV Operations

Three frequency levels of SV operations were modeled for each forecast year (2018 and 2025). The SVO team used projections from AST as well as their own research findings to develop estimates for the number of yearly SV operations in 2018 and 2025 (FAA, 2013). Since there is high uncertainty in forecasting future space operations, the team selected three values to represent varying likelihood of SV operations. The values used for each frequency level were defined using the following assumptions:

- Low Frequency – 90% confidence that this frequency of space operations or higher will occur by the forecasted year,
- Medium Frequency – 50% confidence that this frequency of space operations or higher will occur by the forecasted year, and
- High Frequency – 10% confidence that this frequency of space operations or higher will occur by the forecasted year.

Analysts in the SVO program used the yearly projections for each frequency level to create potential schedules of space operations for each day of the year. The schedules included the time, location, and type of SV operation and were built with some key constraints such as projected yearly operations by spaceport, planned SV operators at each spaceport, and likely time of day necessary to meet the operation's mission (such as daylight hours for tourist flights). The complete set of daily schedules will be used for a study conducted by Stanford University to quantify annual effects of space operations on the NAS.

This study utilized a subset of these schedules. One daily schedule per forecasted year (2018 and 2025) and SV operations level (Low, Medium, and High) was simulated, resulting in six different scenarios with varying SV operations occurring at different locations in the United States. Using these projected schedules allowed researchers to establish scenario assumptions for the SV operations such as time, location, and type of operation. The daily schedules used in this activity were chosen such that the number of SV operations was equal to the average number of daily operations calculated from the team's yearly projections. Appendix B contains a detailed description of the SV operations as well as screenshots from AirTOp of the airspace closures in each simulation scenario.

It is important to note that the six days simulated contain different SV operations in different locations in the United States. The launch of certain vehicles may have caused more disruptive airspace closures than others, and launches or reentries in some areas of the NAS (such as the Northeast or in close proximity to a major airport) may have been more impactful than in other regions. As a result, a direct comparison was not made between the six simulation days.

2.2.2.6 Air Traffic Control (ATC) Procedures

Both current and proposed ATC procedures were modeled in this study to answer the two research questions stated in Section 1.1. Today, the FAA ensures the safety of aircraft during an SV operation by collaborating with operation planners (such as range and SV operators) to determine which airspaces should be closed to air traffic. Closed airspaces typically include pre-defined SAAs such as warning and restricted airspaces as well as new hazard areas created specifically for the operation. Air traffic avoids these closed airspaces during an activation period defined in a NOTAM. Once the activation period expires, the airspace restriction is lifted, and air traffic can use the airspace as normal.

Currently, NOTAMs are the primary resource used to notify NAS users of active airspace closures for special activities occurring within the NAS. These notices are published in advance, and many airlines preemptively change their flight route to avoid the blocked airspace. When necessary, controllers will direct air traffic around these airspace blockages as efficiently as possible. For the simulations in this study, it was assumed that no preemptive route changes were made and that NextGen improvements such as Area Route Navigation (RNAV) allowed for more optimal rerouting in the forecast years. Simulated flights predicted to enter a closed airspace took the shortest path to reroute around the airspace closure when possible.

To model airspace closures used today, historical launches involving the same or similar operations as those included in the simulation scenarios were identified. The NOTAMs associated with these operations were obtained from the FAA's NOTAM Search website (NOTAM Search, 2014) and used to define the shape and duration of the airspace closures modeled in this study. A list of the relevant NOTAMs used as input for the simulation can be found in Appendix A. Some adjustments were made to the duration of the airspace closure when the operation was a test launch or occurred within restricted airspaces that were known to be continually active (such as restricted airspaces surrounding White Sands Missile Range). Also, input from AST and other Subject Matter Experts (SME) was used to define the airspace closure boundaries and timing for vehicles that have not yet flown an operational mission such as Virgin Galactic's SpaceShip 2 and XCOR's Lynx.

The current method for defining airspace closures during SV launch and reentry operations is defined in Dr. Paul Wilde's briefing entitled "Aircraft Protection Analysis for Launch and Reentry." The use of pre-defined warning and restricted airspaces often results in larger amounts of airspace being closed to air traffic than is necessary to maintain safety. While the static and conservative nature of today's airspace closures ensures the safety of NAS users, it does not allow for flexibility in ATC maneuvering and significantly reduces the efficiency of flights during SV operations (Young and Kee, 2014). Stanford University's Aerospace Design Lab proposed using dynamic airspace closures based on probabilistic SV trajectory profiles to minimize the size and duration of airspace closures while maintaining a high level of safety for flights operating near an SV launch or reentry site. The 4D compact envelopes were designed to be both temporally and spatially dynamic which will allow for instantaneous updates in accordance with both the mode and mission of SV operation (Colvin and Alonso, 2015).

For a comparison of these two methods for closing airspace, Figure 3. SAA for an Orbital Sciences Pegasus Launch at Wallops Flight Facility illustrates the difference between a current set of airspace closures and Stanford University's dynamic 4D compact envelopes. The figure shows an example of airspaces closed for an Orbital Sciences Pegasus launch from Wallops Flight Facility[*]. Airspaces defined

[*] The type of SV operation plays an important role in determining the size, shape, and timing of the SAAs used to protect air traffic during SV operations.

in red are the actual SAAs and hazard areas used in a historical launch, and the 4D compact envelopes proposed for the same operation are presented in blue.

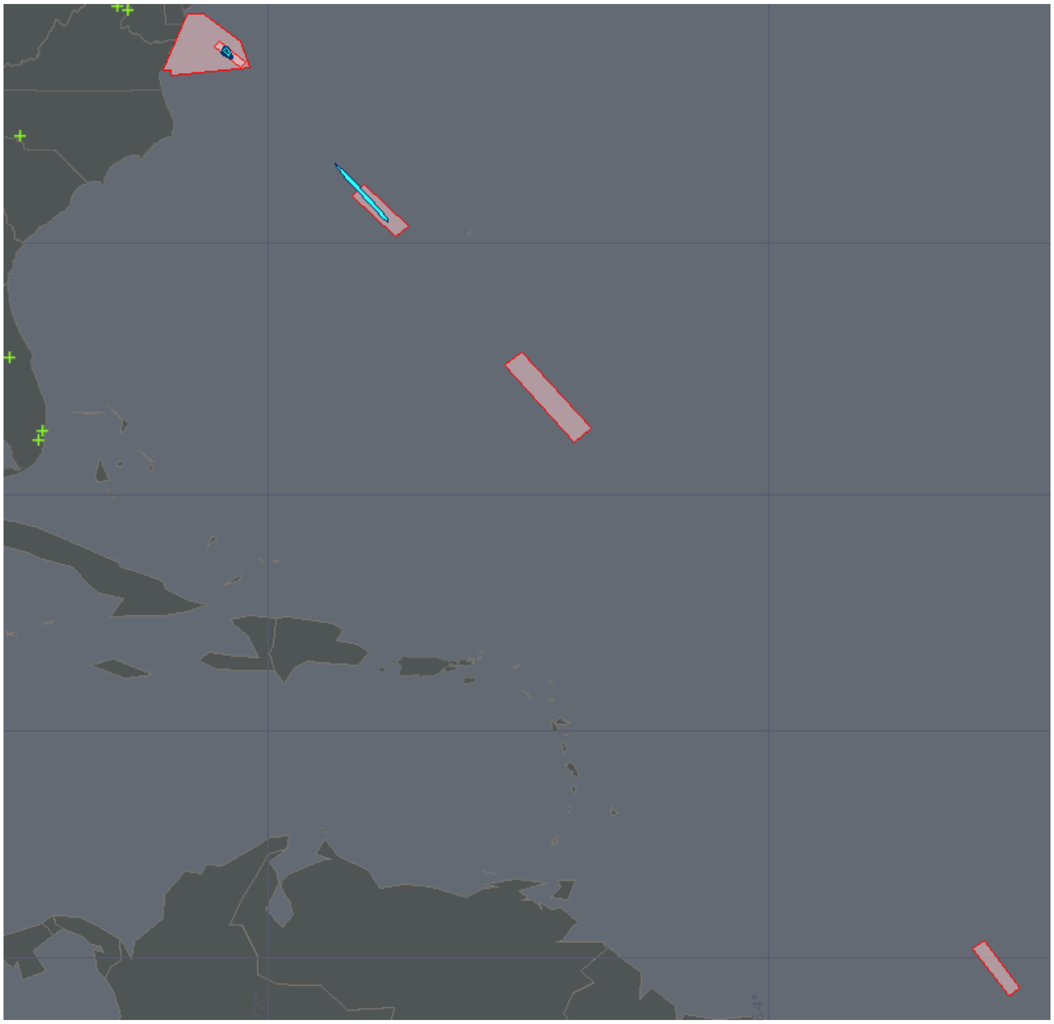

Figure 3. SAA for an Orbital Sciences Pegasus Launch at Wallops Flight Facility

2.2.3 Simulation Scenarios

Table 1 contains information on each scenario simulated in this study. For each simulation scenario, the table defines the following factors: airspace closure strategy (SAAs and hazard areas used today or Stanford University's 4D compact envelopes); forecast year; number of simulated flights; level and number of SV operations; and the ARTCCs protecting their airspace during these SV operations. In addition to showing a quick comparison of simulated scenario components, this table also highlights the key components used to construct the simulation scenarios. It is clear from Table 1 that two types of comparisons can be made: a comparison between each of the six simulation days and its corresponding baseline; and a comparison between airspace closure strategies used on the same simulation day. As shown below, the number of SV operations and their locations are different in each simulation day which does not allow for a direct comparison of the days.

Table 1: Simulated Scenarios Comparison

Scenario ID	Airspace Closure Strategy	Forecast Year	Number of Flights	SV Operations Level	Number of SV Operations	ARTCC Location of SV Operations
BL2018	None	2018	51,749	None	0	N/A
BL2025	None	2025	56,478	None	0	N/A
Current Day 1	Current	2018	51,749	Low	3	ZAB, ZDC, ZFW, ZHU
4DE Day 1	4D Compact Envelopes					
Current Day 2	Current	2018	51,749	Medium	4	ZAB, ZDC, ZLA, ZOA
4DE Day 2	4D Compact Envelopes					
Current Day 3	Current	2018	51,749	High	7	ZAB, ZDV, ZFW, ZHU, ZJX, ZMA
4DE Day 3	4D Compact Envelopes					
Current Day 4	Current	2025	56,478	Low	6	ZAB, ZAN, ZFW, ZHU, ZJX, ZLA, ZMA
4DE Day 4	4D Compact Envelopes					
Current Day 5	Current	2025	56,478	Medium	8	ZAB, ZDV, ZFW, ZHU, ZLA
4DE Day 5	4D Compact Envelopes					
Current Day 6	Current	2025	56,478	High	15	ZAN, ZDC, ZDV, ZFW, ZHN, ZHU, ZJX, ZKC, ZLA, ZMA, ZOA
4DE Day 6	4D Compact Envelopes					

2.2.4 Assumptions and Limitations

The following list addresses some assumptions and limitations acknowledged throughout this study.

- The air traffic and SV operations in the 2025 scenarios were not a superset of those in the 2018 scenarios, although the number of flights and SV operations were greater. Similarly, the three levels of space traffic did not build on the lower levels; for example, the set of operations in the medium level scenario did not contain the SV operations in the low level scenario. Therefore, the simulation scenarios with SV operations should only be compared to their corresponding baseline and not to other scenarios with a different forecast year or level of space traffic.
- The simulation modeled only En Route rerouting maneuvers performed in response to blocked airspace from an SV operation. Impacts to TRACON and ground operations as well as secondary effects of rerouting in En Route airspace such as conflicts, traffic management initiatives, and sector boundary changes were not simulated. As a result, only direct effects to rerouted flights can be quantified in this study. No conclusions were made on the overall NAS impact.
- Each of the six simulation scenarios represent one potential day of SV operations, selected from the yearly schedule discussed in Section 2.2.2.5. There was no variation of SV operations within a given day; however, there was variation between days in the annual schedules. Stanford University is using these schedules to conduct a complementary fast-time simulation study to quantify the annual effects of increased SV operations in forecast years.
- Traffic management decisions were not impacted by controller workload or sector occupancy thresholds. Instead, the demand on these resources was quantified and used to identify potential problems caused by increased SV operations.
- No expected changes in airport capacity, ATC procedures, or airspace boundaries in the modeled forecast years were represented in this study. If there is sufficient interest, this detail could be added to a future follow-up study.
- No convective weather or atmospheric data (i.e. temperature and wind) were modeled in any of the simulation scenarios.
- The actual trajectories of the space vehicles were not modeled; they were assumed to lie within the boundaries of restricted airspace and, thus, did not need to be modeled.
- Flights that were rerouted to avoid entering a restricted airspace (e.g., current procedures or 4D compact envelopes) were rerouted on an optimal path to minimize the extra distance flown. In the simulation, these flights did not join an existing NAS route as they may do today.
- The rerouting capability used in this simulation did not allow some flights to be rerouted to avoid the closed airspaces. This is a limitation of the optimal rerouting algorithm chosen for this study, and affected flights were documented. A future study could attempt to mitigate this shortfall.
- No VFR traffic was simulated in this study.
- Conflicts between aircraft were not resolved in the simulations. If there is sufficient interest, this detail could be added to a future follow-up study.
- The schedule of SV operations used in this study was developed with the most current information and available projections of future space operations.
- Carrier aircraft of space vehicles, such as Virgin Galactic’s White Knight 2, were assumed to be certified as aircraft by the forecast years modeled. As a result, hazard areas for these operations did not include the captive carry portion of the flight.
- Stanford University’s 4D compact envelopes were used in this study to illustrate the potential benefits of changing today’s method of blocking airspace for SV operations. Several other mitigation strategies have been proposed and may be viable solutions. Stanford’s concept was chosen as an example of one of these strategies and requires more extensive research to prove its viability in the NAS.

3 Analysis

This section documents the analysis performed for this study with a brief description of the methods employed in Section **Error! Reference source not found.** and the analysis results in Section **Error! Reference source not found.**.

3.1 *Methods of Analysis*

Output from the AirTOp model was collected from files created during the simulations. These included statistics on distance flown, flight duration, and fuel burn per flight, as well as sector occupancy counts. The output of the simulation scenarios were compared both descriptively and inferentially against those of their respective baseline scenarios to determine the potential effects of SV operations on the NAS and the benefits of one mitigation strategy.

The analysis answered both research questions posed in Section 1.1 using the metrics defined in Section 2.1. To quantify the effects of increased space operations on the efficiency of En Route flights using current airspace restrictions, a comparison was made of flights from scenarios representing today's airspace closures (referred to as "Current" scenarios) against flights from a baseline scenario with no SV operations (referred to as "Baseline" scenarios). Similar statistics were calculated to identify potential benefits of using a new procedure to mitigate this impact; for this analysis, the same Current scenarios were compared against those in which Stanford University's 4D compact envelopes were modeled (referred to as "4DE" scenarios).

Once the differences in flight efficiency were obtained, a paired *t*-test was performed to evaluate their statistical significance. Performing this statistical technique examined the distribution of differences in flight efficiency metrics between two scenarios and tested if the mean of the differences was statistically different from zero. The results from the paired *t*-tests were provided in tables. The mean difference indicated which scenario simulated more efficient flight patterns, and the *p*-value indicated whether or not this difference was statistically significant. The presented *p*-value was the probability of observing a discrepancy in means at least as large as that observed in the data set, even if there was no underlying difference in the means. In this study, a *p*-value less than 0.05 was considered to indicate statistical significance.

Another analysis was performed to examine the potential effects on sector capacity and controller workload. Sector occupancy values were measured in 15 minute increments for the simulated scenarios and compared to known MAP thresholds. The rerouting maneuvers implemented in the simulation represented the smallest possible path deviations to successfully reroute flights to avoid hazard areas and did not consider MAP value assignments. Also, the simulation did not include sector changes such as combining or joining two adjacent sectors to meet the demands of the rerouted traffic on sector capacity.
Therefore, if it was found that these rerouting maneuvers caused excessive MAP threshold violations, we could draw several conclusions. In a real-world situation, traffic management policies would not allow MAP values to be greatly or frequently exceeded, and ATC would employ alternate solutions. Since these solutions would not be the smallest possible path deviations, we can surmise that they would have even greater impacts than those demonstrated in the simulated scenarios. Thus, frequently exceeding sector MAP values would correlate to higher controller workload in those sectors. In addition, MAP values were measured for each defined En Route sector in the NAS. In actual operations, some of these defined sectors are combined and worked by a single controller when traffic demand permits. Thus, even when sector flight counts did not exceed MAP values, it is possible that additional ATC staffing would be required to operate these normally combined sectors independently when combined flight counts increased. These findings would point to the need for carefully constructed solutions to reroute traffic while meeting traffic management restrictions and optimizing ATC staffing.

It is important to note again that a different set of flights and SV operations were modeled in the 2018 scenarios than in the 2025 scenarios, and no comparison between 2018 and 2025 scenarios or between different scenario days was made to form conclusions for this study.

3.2 *Results*

This section presents the inferential statistics used to quantify the effects of SV operations on En Route NAS and the potential benefits of using one proposed mitigation strategy (Stanford University's 4D compact envelopes). There were 51,749 flights simulated in each of the 2018 scenarios and 56,478 flights in the 2025 scenarios. However, the analysis excluded 2,008 flights from the 2018 scenarios and 2,037 flights from the 2025 scenarios due to known fuel burn modeling issues with two aircraft types (PA-28 and fighter jet). Thus, the analytical results discussed in the remainder of Section 3 were based on 49,741 flights from the 2018 scenarios and 54,441 flights from the 2025 scenarios.

Researchers focused their detailed analysis on flights directly affected by the SV operations. Section 3.2.1 provides the flight efficiency statistics of rerouted flights which were used to answer this study's research questions. Section 3.2.2 discusses the change in flight efficiency and sector throughput due to the introduction of SV operations in the NAS; Section 3.2.3 provides similar statistics to show potential effects on the NAS when Stanford University's 4D compact envelopes were used during SV operations instead of today's typical airspace closures.

3.2.1 Flight Efficiency Statistics for Rerouted Flights

A total of 395 unique flights were rerouted in at least one 2018 simulation scenario, and 849 in at least one 2025 scenario. The number of flights rerouted in each 2018 and 2025 scenarios is found in Figure 4 and Figure 5. More flights were rerouted in the Current scenarios than in the 4DE scenarios for both 2018 and 2025 forecast years. In fact, Days 1 and 2 of the 2018 4DE scenarios were the same as the 2018 Baseline scenario (BL2018) since no flights were rerouted in those scenarios. In subsequent analysis, 12 of the rerouted flights in the 2018 scenarios had to be excluded, and 13 flights in the 2025 scenarios excluded, due to the fuel burn modeling shortfalls mentioned above. Flight efficiency statistics for the remaining 383 (2018 scenarios) and 836 flights (2025 scenarios) are listed in Table 2 and Table 3, respectively.

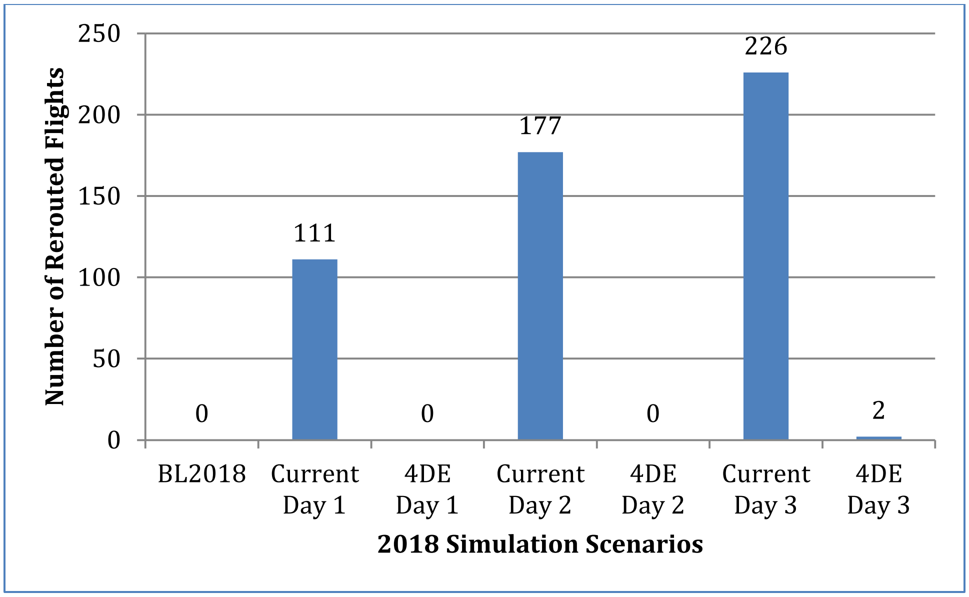

Figure 4. Number of Flights Rerouted in the 2018 Simulation Scenarios

Table 2. Flight Efficiency Averages for Rerouted Flights in the 2018 Simulation Scenarios

Scenario ID	Avg. Total Distance per Flight (NM)	Avg. Fuel Burned per Flight (lbs)	Avg. Flight Duration per Flight (min)
BL2018	1475.73	27164.60	207.71
Current Day 1 (3 SV Ops)	1479.22	27207.67	208.11
4DE Day 1 (3 SV Ops)	1475.73	27164.60	207.71
Current Day 2 (4 SV Ops)	1485.12	27364.49	208.91
4DE Day 2 (4 SV Ops)	1475.73	27164.60	207.71
Current Day 3 (7 SV Ops)	1483.38	27258.08	208.83
4DE Day 3 (7 SV Ops)	1475.73	27164.66	207.71

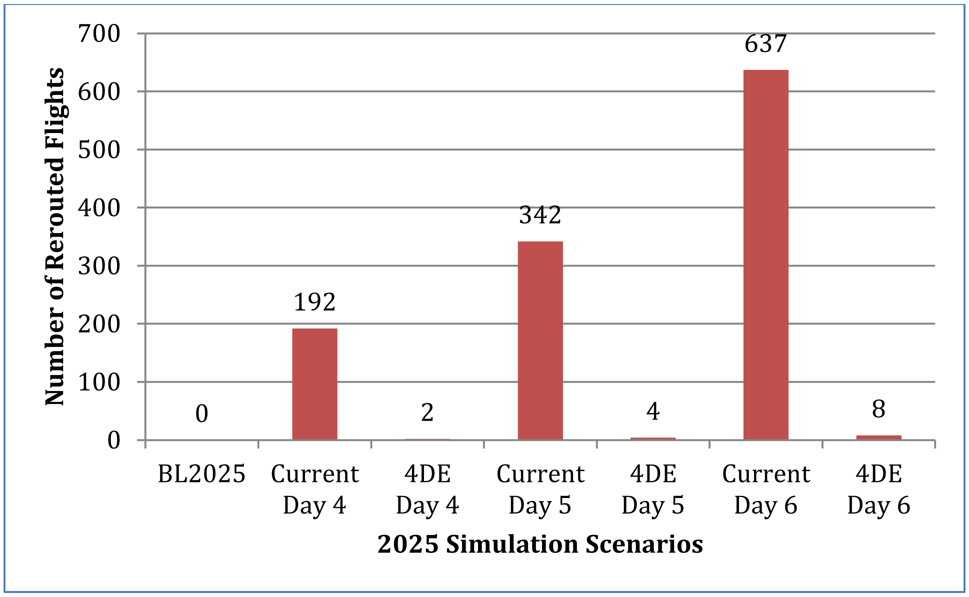

Figure 5. Number of Flights Rerouted in the 2025 Simulation Scenarios

Table 3. Flight Efficiency Averages for Rerouted Flights in the 2025 Simulation Scenarios

Scenario ID	Avg. Total Distance per Flight (NM)	Avg. Fuel Burned per Flight (lbs)	Avg. Flight Duration per Flight (min)
BL2025	1191.23	16602.23	172.45
Current Day 4 (6 SV Ops)	1198.56	16684.79	173.75
4DE Day 4 (6 SV Ops)	1191.23	16602.24	172.45
Current Day 5 (8 SV Ops)	1198.28	16695.56	173.44
4DE Day 5 (8 SV Ops)	1191.25	16602.31	172.45
Current Day 6 (15 SV Ops)	1209.89	16802.59	175.01
4DE Day 6 (15 SV Ops)	1191.24	16602.33	172.45

Additional flights should have been rerouted in the simulation but were left unchanged due to limitations in the model's automatic rerouting algorithm. Appendix C provides a count of the interactions between flights and airspace closures in each scenario. Figure 6 and Figure 7 show the total amount of flights in the 2018 and 2025 scenarios, respectively, that were impacted by the SV operations during the simulations and, therefore, should have been rerouted. The values in these figures include flights that were successfully rerouted as well as flights for which the model could not find a viable rerouted path around the closed airspaces. For the latter, the flights stayed on their original flight path and were simulated completely, allowing flight efficiency values to be calculated. This unsuccessful rerouting behavior was observed to be typical of flights entering or departing an airport's TRACON airspace where rerouting maneuverability was limited by the model's algorithm. Since the impact to these flights cannot be calculated, the results of this study are limited to the impact of SV operations on flights in the En Route phase of flight.

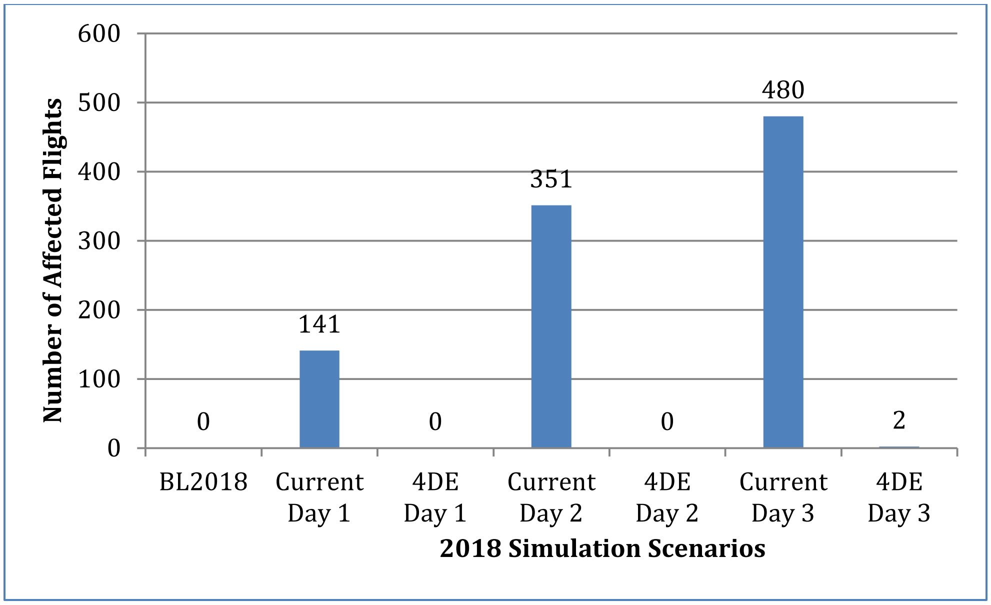

Figure 6. Total Number of Affected Flights in the 2018 Scenarios

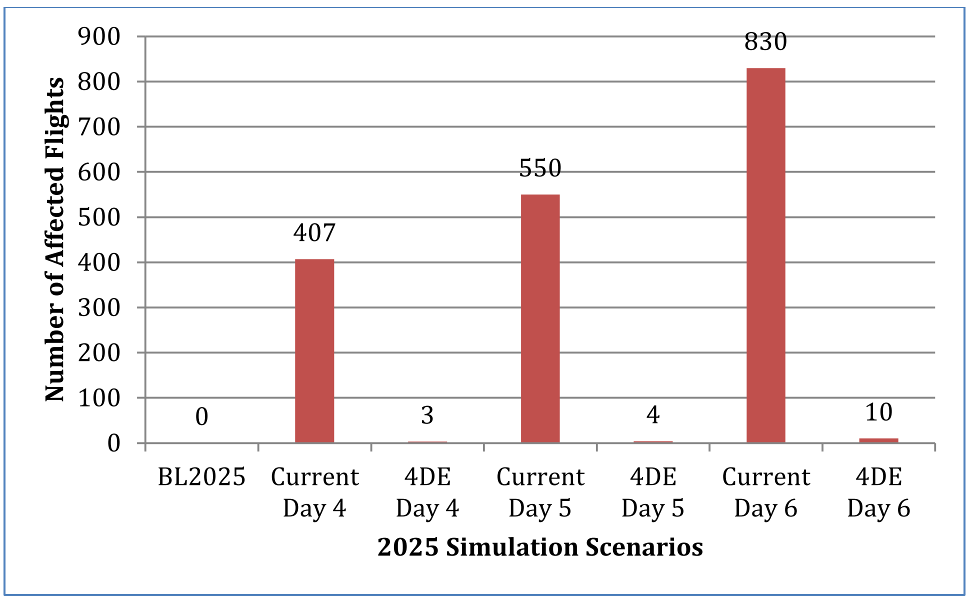

Figure 7. Total Number of Affected Flights in the 2025 Scenarios

3.2.2 Effects of Increased SV Operations on the NAS

To quantify the effects of increased SV operations on the NAS using today's typical airspace closures, two analyses were performed to compare the Current simulation scenarios against their corresponding Baseline scenarios (BL2018 and BL2025). First, the efficiency of flights simulated around today's airspace closures on six separate days of potential SV operations was compared against those of flights simulated with no launches or reentries in the NAS (thus, no airspace closures). Researchers studied changes to the efficiency of flights that were rerouted to avoid the closed airspaces protecting air traffic from SV operations. Figure 8 through Figure 10 show the differences in average distance flown, fuel burned and duration flown, respectively, for 2018 and 2025 simulation scenarios (2018 scenarios are depicted in blue and 2025 scenarios are shown in red). A paired *t*-test was used to determine the statistical significance of these changes. Table 4 through Table 6 list the mean difference and statistical significance for each scenario. The subpopulation of flights used in these comparisons was kept consistent: 383 flights for all 2018 comparisons, and 836 flights for all 2025 comparisons.

In every simulation scenario, the change in flight efficiency due to the introduction of SV operations was statistically significant. Flights that rerouted around closed airspace in the 2018 scenarios flew an additional 3.49 NM, burned 43.07 lbs more fuel, and flew 0.40 min longer on average during low levels of SV operations on Day 1; flights rerouted around a medium level of SV operations on Day 2 flew 9.39 NM more, burned 199.89 lbs more fuel, and flew 1.20 min longer on average; and rerouted flights flew an average of 7.65 NM farther, burned 93.48 lbs more fuel, and flew 1.12 min longer during high levels of SV operations on Day 3. Likewise, for 2025 scenarios, flights rerouted around closed airspace flew an additional 7.32 NM, burned 82.56 lbs more fuel, and flew 1.31 min longer on average during low levels of SV operations on Day 4; flights rerouted around a medium level of SV operations on Day 5 flew 7.04 NM farther, burned 93.33 lbs more fuel, and flew 1.00 min longer on average; and rerouted flights flew an average of 18.66 NM farther, burned 200.36 lbs more fuel, and flew 2.56 min longer during high levels of SV operations on Day 6.

The impact to flights in the Current Day 2 scenario was larger than on the other 2018 simulation days. This was because several flights traveling from Australia, New Zealand, and Hawaii were rerouted around closed airspace off the Pacific coast of the United States for two SV operations. The closed airspaces are large and result in a lengthy reroute for these flights.

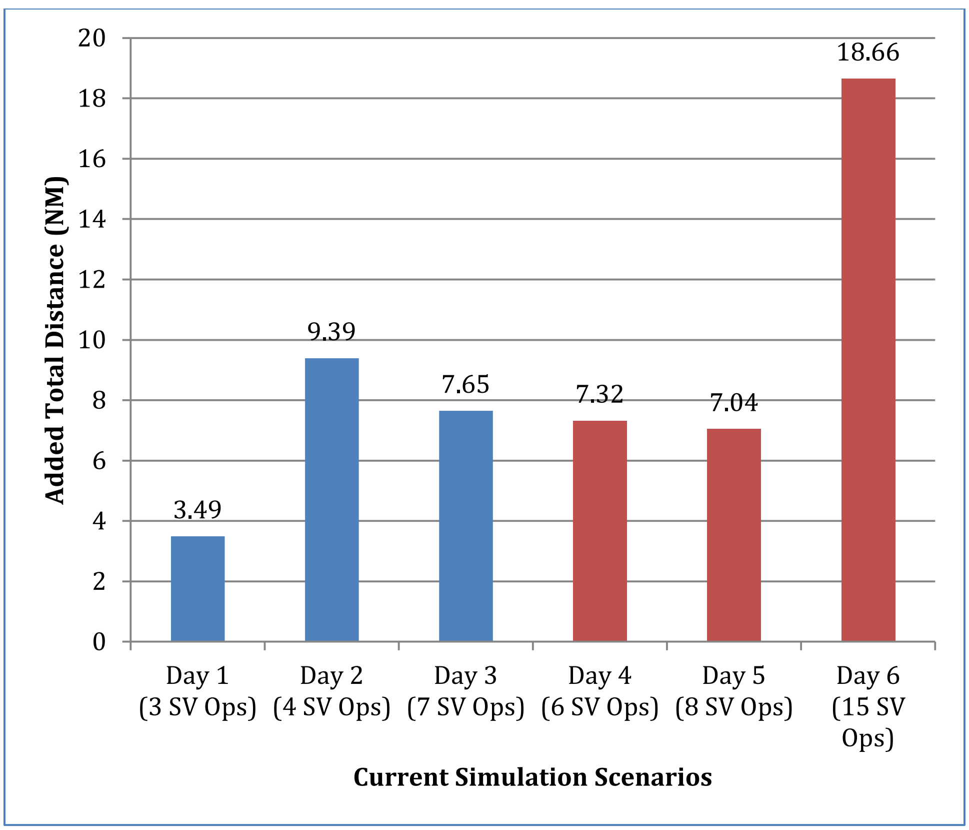

Figure 8. Difference in Average Flight Distance from Baseline Simulation Scenarios

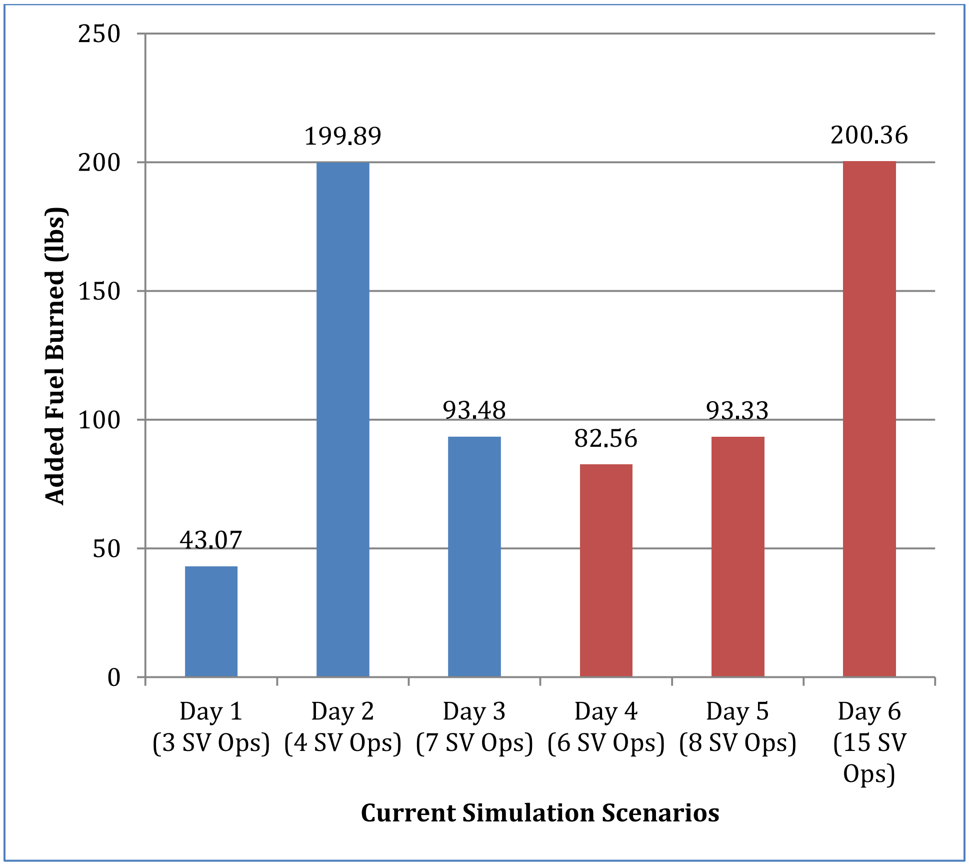

Figure 9. Difference in Average Fuel Burned from Baseline Simulation Scenarios

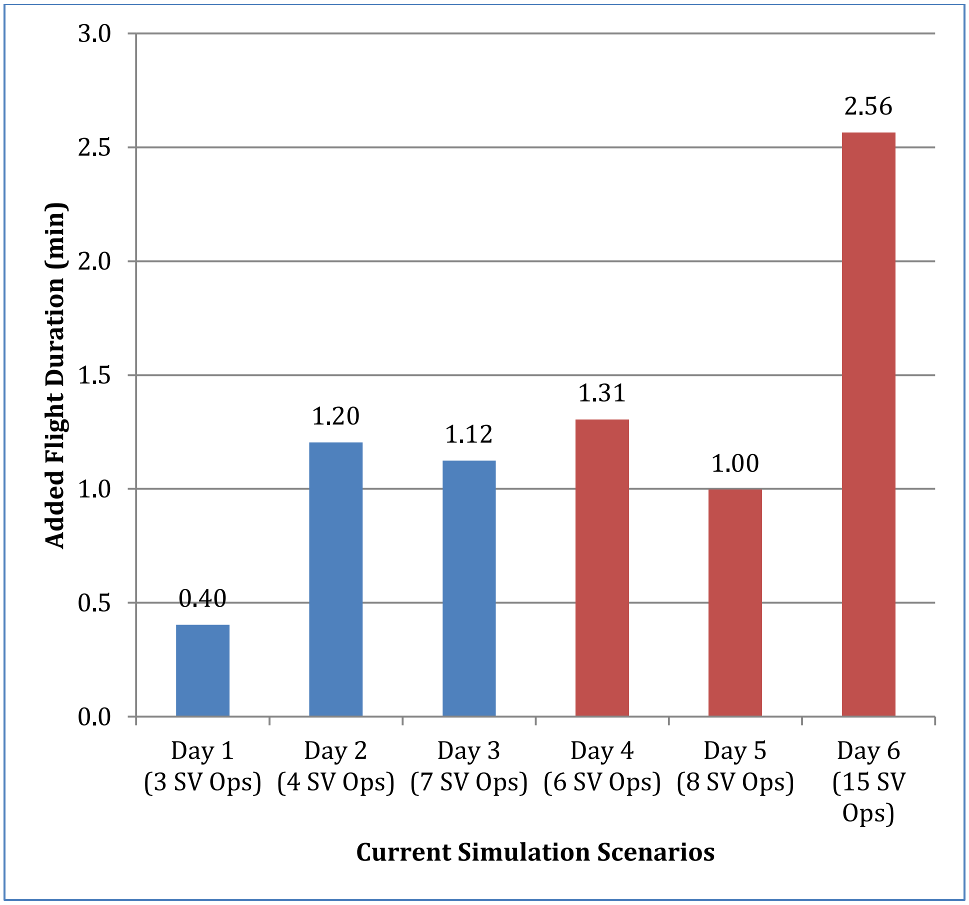

Figure 10. Difference in Average Flight Duration from Baseline Simulation Scenarios

Table 4. Paired *t*-Test for Total Distance Flown (NM) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob > t	Significantly Different? (α level = 0.05)
Current Day 1 - BL2018	3.49	<.0001	Yes
Current Day 2 - BL2018	9.39	<.0001	Yes
Current Day 3 - BL2018	7.65	<.0001	Yes
Current Day 4 - BL2025	7.32	<.0001	Yes
Current Day 5 - BL2025	7.04	<.0001	Yes
Current Day 6 - BL2025	18.66	<.0001	Yes

Table 5. Paired *t*-Test for Total Fuel Burned (lbs) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob > t	Significantly Different? (α level = 0.05)
Current Day 1 - BL2018	43.07	<.0001	Yes
Current Day 2 - BL2018	199.89	<.0001	Yes
Current Day 3 - BL2018	93.48	<.0001	Yes
Current Day 4 - BL2025	82.56	<.0001	Yes
Current Day 5 - BL2025	93.33	<.0001	Yes
Current Day 6 - BL2025	200.36	<.0001	Yes

Table 6. Paired *t*-Test for Total Duration Flown (min) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob > t	Significantly Different? (α level = 0.05)
Current Day 1 - BL2018	0.40	0.00430	Yes
Current Day 2 - BL2018	1.20	<.0001	Yes
Current Day 3 - BL2018	1.12	<.0001	Yes
Current Day 4 - BL2025	1.31	<.0001	Yes
Current Day 5 - BL2025	1.00	<.0001	Yes
Current Day 6 - BL2025	2.56	<.0001	Yes

Next, the throughput of all NAS sectors was investigated to identify possible capacity and workload issues that might be caused by flights rerouting around large restricted airspaces. The maximum number of flights in each sector within a 15 minute time period (referred to as max occupancy) was calculated for all simulation scenarios and compared against the MAP value assigned to the sector. The number of MAP threshold violations was counted for the Baseline, Current and 4DE simulation scenarios, and changes to these counts between scenarios are reported by sector in Table 24 and Table 25 in Appendix D. Sectors whose maximum occupancy exceeded the MAP threshold the same amount of times in all scenarios were not included in these tables. An aggregate of these changes from the baseline scenarios is presented by ARTCC in Table 7 and Table 8 below.

Table 7. Aggregate Difference in MAP Threshold Violations by ARTCC in 2018 Scenarios

ARTCC	Number of Affected Sectors	Current Procedures			4D Compact Envelopes		
		Day 1	Day 2	Day 3	Day 1	Day 2	Day 3
ZAB	3	4	0	0	0	0	0
ZDC	2	0	0	0	0	0	0
ZDV	2	0	0	2	0	0	0
ZHU	2	1	0	0	0	0	0
ZLA	1	0	-1	0	0	0	0
ZMA	2	0	0	4	0	0	0
ZME	1	0	0	-1	0	0	0
ZMP	2	0	0	2	0	0	0
ZOA	1	0	0	1	0	0	0
ZTL	3	-1	0	0	0	0	0

Table 8. Aggregate Difference in MAP Threshold Violations by ARTCC in 2025 Scenarios

ARTCC	Number of Affected Sectors	Current Procedures			4D Compact Envelopes		
		Day 4	Day 5	Day 6	Day 4	Day 5	Day 6
ZAB	9	4	1	0	0	0	0
ZAU	2	0	0	0	0	0	0
ZBW	2	0	0	0	0	0	0
ZDC	5	-1	0	1	0	0	0
ZDV	6	1	5	-1	0	0	0
ZFW	1	0	0	1	0	0	0
ZHU	7	-2	-2	3	0	0	0
ZID	2	-1	0	1	0	0	0
ZJX	6	2	0	1	0	0	0
ZKC	2	1	0	0	0	0	0
ZLA	8	0	0	-3	0	0	0
ZLC	2	0	0	0	0	0	0
ZMA	3	-1	0	5	0	0	0
ZME	1	0	0	1	0	0	0
ZMP	2	1	1	0	0	0	0
ZNY	3	1	-1	-2	0	0	0
ZOA	3	1	0	1	0	0	0
ZOB	2	1	-1	0	0	0	0
ZSE	1	1	0	0	0	0	0
ZTL	8	0	0	-2	0	0	0

Decreases in MAP threshold violations were likely due to part of the airspace being closed for an SV operation. An increase in MAP threshold violations indicated a higher demand on controller workload since a more complicated plan for rerouting aircraft would be necessary to maintain a manageable sector throughput. Coordination between sectors and ARTCCs would be necessary to handle rerouted paths around the closed airspaces.

For example, Jacksonville ARTCC (ZJX) closed airspace in the Day 6 simulation scenarios first for a Falcon 9 launch at Spaceport Georgia, then for a launch of Spaceship 2 at Titusville, FL, and finally for a Falcon 9 launch at Cape Canaveral, FL. The airspace closures in ZJX during these operations caused changes to throughput in several ZJX sectors. An increase in MAP threshold violations was seen in sectors ZJX049, ZJX050, and ZJX076, and a decrease was observed in sectors ZJX058, ZJX065, and ZJX068. Figure 11 illustrates these sectors as well as the closed airspaces (increases in MAP threshold violations are in green, decreases are in red, and the closed airspaces are in yellow). During the Falcon 9 launch from Spaceport Georgia, airspace within ZJX068 was closed, resulting in a decrease of throughput and, thus, MAP threshold violations in that sector. However, flights had to reroute into neighboring sectors ZJX049, ZJX050, and ZJX076 to avoid this constrained area, increasing the throughput in these sectors and, ultimately, the number of MAP threshold violations. These maneuvers would require additional coordination between sector controllers as well as possible sector staffing changes; thus, an increase in controller workload would be expected to protect air traffic during the SV operations.

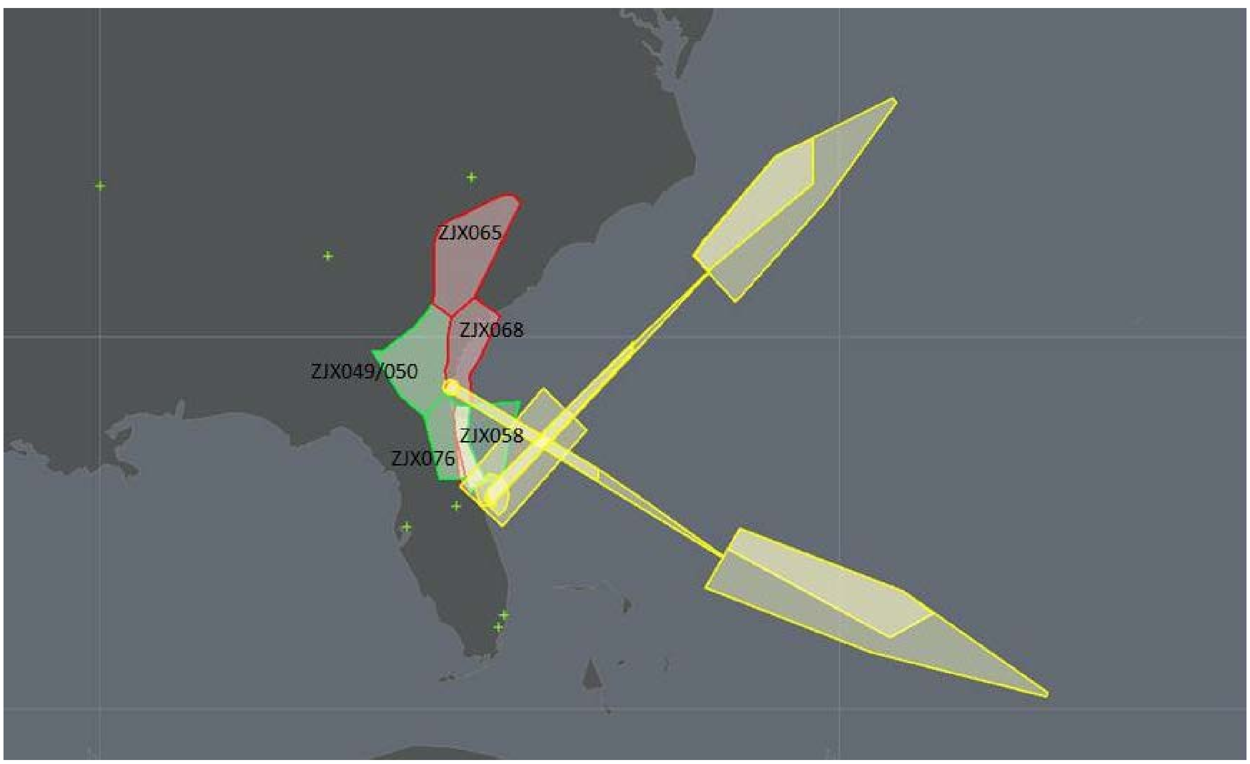

Figure 11. ZJX Sectors with Changes to MAP threshold violations and Local Airspace Closures for Day 6 Simulation Scenarios

3.2.3 Potential Benefits of Dynamic Airspace Closures

A similar analysis was performed to evaluate the changes to flight efficiency and sector throughput when today's airspace closures are replaced with Stanford University's concept of 4D compact envelopes. As shown in Figure 2, the 4DE simulation scenarios were compared against the Current simulation scenarios with corresponding simulation day.

The difference in average flight efficiency per flight was calculated for total distance flown, fuel burned, and duration flown. The results of this comparison are presented in Figure 12 through Figure 14. A paired *t*-test was performed for each metric to determine the statistical significance of the differences in flight efficiency. Table 9 through Table 11 list the results of each comparison. For all comparisons, the difference between flight efficiency in the Current scenarios and the 4DE scenarios was statistically significant.

Since no flights were rerouted during SV operations on Days 1 and 2 in the 4DE scenarios, no impact to flight efficiency was measured when the 4D compact envelopes were used. Flights rerouted due to SV operations on Day 3 saved on average 7.64 NM, 93.42 lbs of fuel, and 1.12 min. Flights rerouted on Day 4 saved on average 7.32 NM, 82.56 lbs of fuel, and 1.31 min of flight time; flights rerouted on Day 5 saved on average 7.03 NM, 93.24 lbs of fuel, and 0.99 min; and rerouted flights on Day 6 saved on average 18.65 NM, 200.26 lbs of fuel, and 2.56 min of flight time.

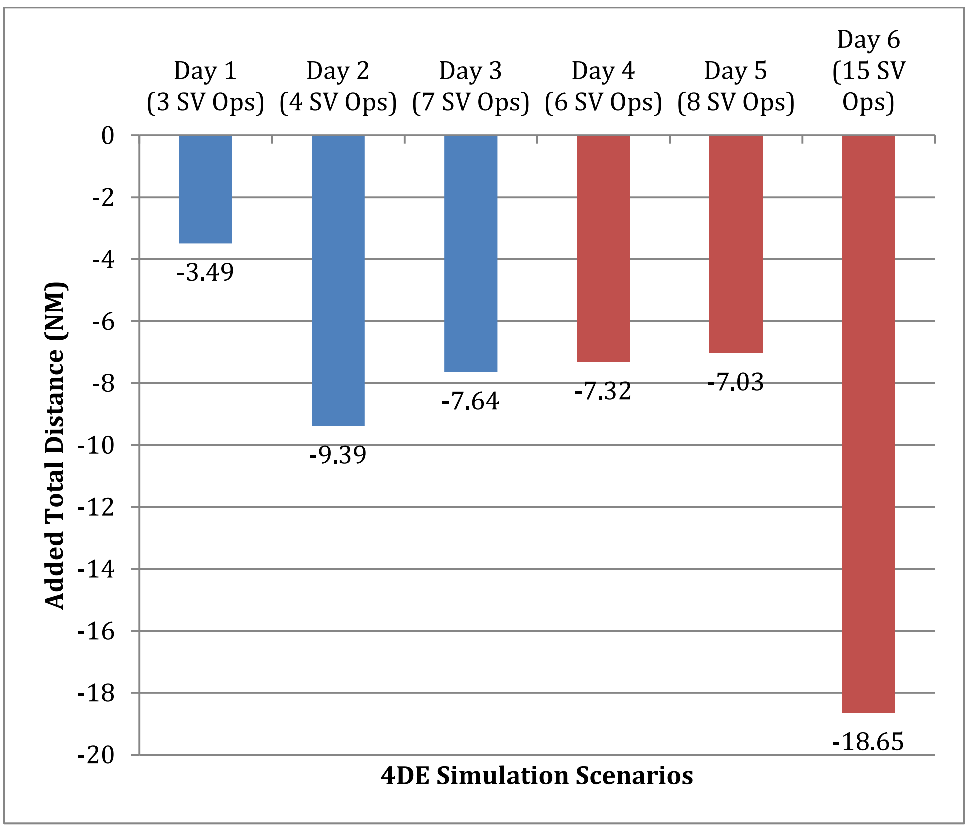

Figure 12. Difference in Average Flight Distance from Current Simulation Scenarios

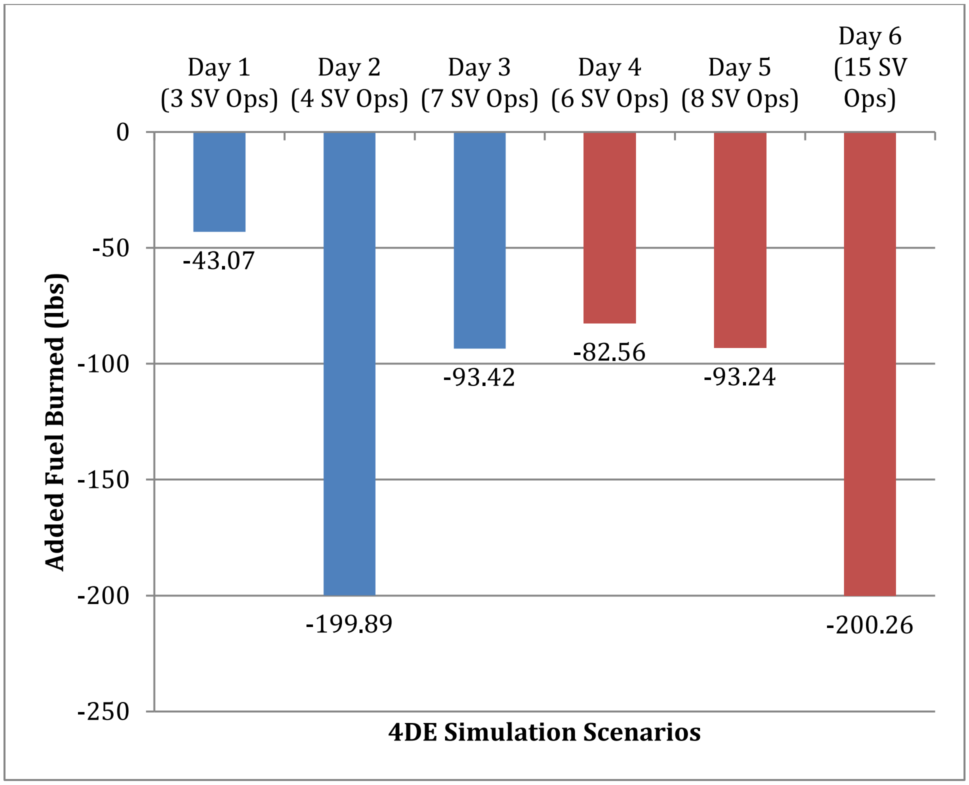

Figure 13. Difference in Average Fuel Burned from Current Simulation Scenarios

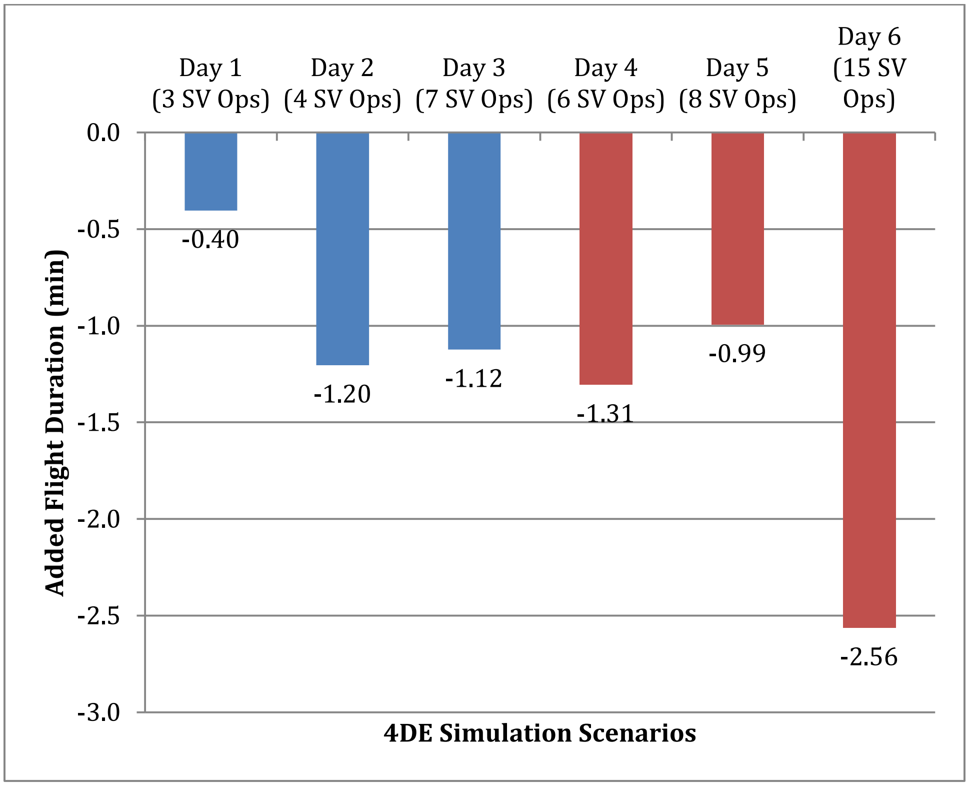

Figure 14. Difference in Average Flight Duration from Current Simulation Scenarios

Table 9. Paired *t*-Test for Total Distance Flown (NM) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob < t	Significantly Different? (α level = 0.05)
4DE Day 1 – Current Day 1	-3.49	<.0001	Yes
4DE Day 2 – Current Day 2	-9.39	<.0001	Yes
4DE Day 3 – Current Day 3	-7.64	<.0001	Yes
4DE Day 4 – Current Day 4	-7.32	<.0001	Yes
4DE Day 5 – Current Day 5	-7.03	<.0001	Yes
4DE Day 6 – Current Day 6	-18.65	<.0001	Yes

Table 10. Paired *t*-Test for Total Fuel Burned (lbs) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob < t	Significantly Different? (α level = 0.05)
4DE Day 1 – Current Day 1	-43.07	<.0001	Yes
4DE Day 2 – Current Day 2	-199.89	<.0001	Yes
4DE Day 3 – Current Day 3	-93.42	<.0001	Yes
4DE Day 4 – Current Day 4	-82.56	<.0001	Yes
4DE Day 5 – Current Day 5	-93.24	<.0001	Yes
4DE Day 6 – Current Day 6	-200.26	<.0001	Yes

Table 11. Paired *t*-Test for Total Duration Flown (min) Compared to Baseline Scenarios

Comparison	Mean Difference	Prob < t	Significantly Different? (α level = 0.05)
4DE Day 1 – Current Day 1	-0.40	0.00430	Yes
4DE Day 2 – Current Day 2	-1.20	<.0001	Yes
4DE Day 3 – Current Day 3	-1.12	<.0001	Yes
4DE Day 4 – Current Day 4	-1.31	<.0001	Yes
4DE Day 5 – Current Day 5	-0.99	<.0001	Yes
4DE Day 6 – Current Day 6	-2.56	<.0001	Yes

Changes to sector throughput were also analyzed for this analysis. As shown in Table 7 and Table 8 in the previous subsection, the number of MAP threshold violations was impacted for many sectors and ARTCCs in the Current simulation scenarios. However, this effect was not observed in any sectors in the 4DE simulation scenarios.

4 Summary

The following sub-sections render the results of this study by providing a summary of the conclusions in Section **Error! Reference source not found.** and recommendations for future work in Section **Error! Reference source not found.**.

4.1 *Conclusions*

Both research questions posed for this study were analyzed and conclusions were formed based on the results presented in Section 3. As a reminder to the reader, the two research questions of this study are restated below.

1. *Using current ATC tools, procedures, and processes, how will the potential increase in SV operations affect En Route traffic in the future?*

2. *Is it possible to minimize the potential effects of SV operations on the NAS by utilizing new airspace closure procedures such as Stanford University's 4D Compact Envelopes concept? If so, what are the potential benefits associated with this change?*

To answer the first research question, a comparison was made between six single-day scenarios in which SV operations were managed using today's airspace closures (Current scenarios) and those with no SV operations in the NAS (Baseline scenarios). Differences in flight efficiency and sector throughput metrics were calculated.

Flights that were directly affected by the airspace closures experienced statistically significant changes on all six simulation days, although the change in flight distance, fuel burned, and flight duration varied for each day modeled. Flights that rerouted around closed airspace flew an additional 3.49 to 18.66 nautical miles (NM), burned between 43.07 and 200.36 pounds (lbs) more fuel, and flew between 0.40 and 2.56 minutes (min) longer. These values were based on flights that rerouted within En Route airspace to avoid closed airspaces, excluding flights that were not rerouted in the simulation but would be required to hold or divert to another airport when landing during an SV operation. Therefore, if SV operations in the NAS increase with no change in the use of airspace closures, the impact to flight efficiency would likely be greater than estimated in this study.

Sector capacity as defined by maximum sector occupancy was also calculated and compared against the sector MAP threshold values. The number of MAP threshold violations in the Current scenarios was compared against that of the Baseline scenarios, and it was determined that the number of violations was affected by the introduction of SV operations. It was concluded that this change in sector throughput would result in additional air traffic management actions to safely manage air traffic around the SV operations; controller workload would likely increase due to the coordination required to implement these maneuvers. Additionally, there may be ATC staffing impacts for sectors that experienced a change in traffic demand. Some sectors with increased traffic may be divided into multiple sectors to avoid exceeding the MAP threshold; this would require additional controllers to manage the new airspaces. Similarly, sectors with decreased traffic demand caused by flights rerouting away from the airspace may be joined with adjacent sectors which would reduce staffing needs.

A similar comparison was made between Current and 4DE scenarios to answer the second research question of this study. When Stanford University's 4D Compact Envelopes were used to protect air traffic during SV operations, rerouted flights experienced statistically significant savings on all six simulation days. Flights rerouted around the 4D compact envelopes saved on average 3.49 to 18.65 NM, between 43.07 and 200.26 lbs of fuel, and 0.40 to 2.56 min of flight time. Although these differences were small, a paired *t*-test proved that the use of 4D compact envelopes improved flight efficiency during SV operations by a statistically significant amount. This result was expected as the size of the envelopes and duration of their activation were considerably smaller and shorter than the closed airspaces typically used today. Since impacts to arrival and departure flights were not captured in this study, these flight efficiency benefits are likely an underestimation of the potential savings.

For all six simulation days, the number of instances where sector MAP thresholds were violated when 4D compact envelopes were used was the same as when no SV operations occurred in the NAS. This is because there were very few flights rerouted around the envelopes. As the use of current airspace closures caused many changes to sector throughput, it can be concluded that 4D compact envelopes reduce coordination time for planning reroutes and adjusting staffing requirements during SV operations. This could lead to a decrease in controller workload; however, the workload required to manage the numerous activations and deactivations of closed airspaces necessary for 4D compact envelopes was not studied and could offset any savings in coordination time for reroutes.

4.2 *Recommendations for Next Steps*

Based on this study's findings, some recommendations for follow on research were made. A more detailed analysis of the changes to sector throughput could be conducted to identify specific reroute maneuvers that were problematic in the simulation. Also, effort could be applied to address the modeling limitations that arose in this study regarding flights that could not be rerouted.

The scope of this study did not include a detailed examination of the effects of SV operations on arrival and departure traffic at airports near launch and reentry sites. It is highly recommended that the SVO program perform a fast-time simulation experiment to evaluate SV operations near airports such as Denver International airport. Once the effects of increased SV operations on airport traffic are understood, it is recommended that the current study be expanded to represent all NAS impacts. This research would allow the SVO program to quantify the overall effects on the NAS by including changes to arriving and departing flights as well as traffic management initiatives. A sensitivity analysis could then be performed to determine the year in which adjustments must be made to the NAS to prevent unacceptable effects on safety, capacity and efficiency due to increased SV operations.

Finally, a follow-on fast-time simulation in conjunction with a real-time Human-in-the-Loop (HITL) simulation should be performed to accurately quantify the impact of increased SV operations on controller workload. Fast-time simulation enables analysts to gain some insight into possible effects on controller workload but approximates only certain aspects of nominal human behavior. A HITL would complement the computer model and is recommended to further explore changes to controller workload and staffing requirements caused by increased SV operations across the NAS.

List of Acronyms

4D	Four-Dimensional
ANG-C41	Concept Analysis Branch
ARTCC	Air Route Traffic Control Center
AST	FAA's Office of Commercial Space Transportation
ATC	Air Traffic Control
ATM	Air Traffic Management
CONUS	Continental United States
FAA	Federal Aviation Administration
ft	Feet
lbs	pounds (measure of fuel)
MAP	Monitor Alert Parameter
min	minutes (measure of time)
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NASE	NAS Adaptation Services Environment
NextGen	Next Generation Air Transportation System
NM	Nautical Miles
NOTAM	Notice to Airmen
PDARS	Performance Data Analysis Reporting System
RNAV	Area Route Navigation
SAA	Special Activity Airspace
SV	Space Vehicle
SVO	Space Vehicle Operations Program
TAF	Terminal Area Forecast
TRACON	Terminal Radar Approach Control
UTC	Coordinated Universal Time
ZAN	Anchorage ARTCC
ZHN	Honolulu ARTCC
ZJX	Jacksonville ARTCC

References

AirTOpsoft. (updated 2007) *AirTOp – ATC Fast-Time Simulator and Air Traffic Optimizer*. Retrieved March 31, 2015, from http://www.airtopsoft.com/products.html.

ATAC. (updated 2010) *ATAC-Programs-Performance Data Analysis Reporting System*. Retrieved March 31, 2015, from http://www.atac.com/pdars.html.

Cheng, F., John Gulding, Bryan Baszczewski, and Ruth Galaviz (2011). *An Optimization-Based Sample Day Selection Algorithm for Future Schedule Generation*. 11th AIAA Aviation Technology, Integration, and Operations (ATIO) Conference, Virginia Beach, VA.

Colvin, Thomas and Juan Alonso. (January 2015). *Compact Envelopes and SU-FARM for Integrated Air-and-Space Traffic Management*. 53rd AIAA Aerospace Sciences Meeting, Kissimmee, FL.

Federal Aviation Administration (2013). *Notional Spaceport Growth: Estimates of "Operational" Launch Dates and Rates*. Washington, DC.

Hatton, Kevin. (2013). *Space Vehicle Operations.* Presentation Briefing presented at SVO Technical Interchange Meeting, Atlantic City, NJ.

Hayes, A. (2008). *SMP Presentation 4.1 AIAA 4-16-08.ppt*. Presentation Briefing presented at the Improving Space Operations Workshop, Suitland, MD.

National Aeronautics and Space Administration (NASA) (updated February 15, 2000) *Space Quotes.* Retrieved September 16, 2013, from http://er.jsc.nasa.gov/seh/quotes.html.

NOTAM Search. *NOTAM Archives.* Retrieved November 2014, from https://notams.aim.faa.gov/notamSearch/.

Space Launch Report. *Launch Failure Rates per Year*. Retrieved November 18, 2014, from http://www.spacelaunchreport.com.

Wilde, Paul Ph.D. (August 7, 2014). *Aircraft Protection Analysis for Launch and Re-entry.* Presentation Briefing presented to Air Traffic Control System Command Center, Warrenton, VA.

Young, Jessica and Marie Kee (2014). *SpaceX Falcon 9/Dragon Operations NAS Impact and Operational Analysis*. FAA Technical Note DOT/FAA/TC-TN13/49, Atlantic City, NJ.

Appendix A: Historical NOTAMs

The following SV operations and their associated NOTAMs were used as input to the scenario assumptions in this study. Initial NOTAMs were received from AST and confirmed using the FAA's NOTAM Archive website (NOTAM Search, 2014). Incomplete NOTAM information was found in the archives for those operations listed with an asterisk. Simulation assumptions for those operations were based on known procedures for similar operations at the spaceport as indicated through planning documents or NOTAMs from separate SV operations.

Blue Origin Planned Launch – Van Horn, Texas on August 24, 2011*
NOTAM Facility: ZAB Albuquerque
NOTAM number: FDC 1/3552

Minotaur Planned Launch – Kodiak, Alaska on September 27, 2011*
NOTAM facility: PAZA Anchorage
NOTAM Number: 09/228, FDC 1/2754

NOTAM Facility: ZAK Oakland
NOTAM Number: 09/227

Armadillo Launch – Spaceport America on January 28, 2012
NOTAM Facility: ZAB Albuquerque
NOTAM Number: FDC 2/5779

Atlas Launch – Vandenberg Air Force Base, California on February 11, 2013
NOTAM Facility: ZLA Los Angeles
NOTAM Number: 02/095, 02/192, 02/193, 02/194, 02/195, 02/197

NOTAM Facility: ZAK Oakland
NOTAM Number: 02/096

SpaceX Falcon 9 Launch – Cape Canaveral, Florida on March 1, 2013
NOTAM Facility: ZMA Miami
NOTAM Number: A0177/13, FDC 3/1587

SpaceX Dragon Reentry – Pacific Ocean on March 26, 2013
NOTAM Facility: ZAK Oakland
NOTAM Number: 03/099

NOTAM Facility: ZLA Los Angeles
NOTAM Number: 03/100

Orbital Sciences Pegasus Launch – Vandenberg Air Force Base, California on June 27, 2013*
NOTAM Facility: ZAK Oakland
NOTAM Number: 06/134

SpaceX Falcon 9 Launch – Vandenberg Air Force Base, California on September 29, 2013
NOTAM Facility: ZLA Los Angeles
NOTAM Number: 09/181, 09/183, 09/401, 09/402, 09/403, 09/404, 09/406, 09/459, 09/460

Sounding Rocket Launch – Poker Flat, Alaska on March 3, 2014
NOTAM Facility: ZAN Anchorage
NOTAM Number: 02/144

Antares Launch – Wallops Island, Virginia on July 13, 2014
NOTAM Facility: ZDC Washington DC
NOTAM Number: 07/057

NOTAM Facility: ZNY New York
NOTAM Number: 07/058

Sounding Rocket Launch – White Sands Missile Range, New Mexico on July 22, 2014
NOTAM Facility: ZAB Albuquerque
NOTAM Number: 07/934, 07/940

Appendix B: Simulation Scenarios

This appendix presents detailed information on each of the simulation scenarios. Each scenario contains different SV operations; Table 12 lists the SV operations for the three 2018 simulation days representing low, medium and high levels of SV operations, while Table 13 lists the same information for the three 2025 simulation days. Each table includes the local and Coordinated Universal Time (UTC) times of the launch or reentry operation, spaceport location, space vehicle used in the operation, time of airspace closures for the SV operation (which include warning and/or restricted airspaces as well as other hazard areas), the azimuth of the operation used to produce Stanford University's 4D compact envelopes, and notes on the operation assumptions. Figure 15 through Figure 26 are screenshots from the AirTOp model that show the airspaces closed in each simulation scenario.

Table 12. SV Operations in 2018 Simulation Scenarios

2018 Scenarios							
Day 1 – Low SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes on Assumptions**
9:00	16:00	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 15:50-16:20	0	assume 10min before, 20min after launch based on SME input
11:20	16:20	Wallops	VA	Orbital Sciences Pegasus	W-386 & hazard areas: 16:05-16:47	150	based on Pegasus launch from VAFB on 06/27/2013
14:15	20:15	Midland	TX	XCOR Lynx	hazard area: 20:05-20:35	120	assume 10min before, 20min after launch based on SME input
Day 2 – Medium SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes**
5:30	13:30	Vandenberg Air Force Base	CA	United Launch Alliance Atlas V	W-289S,W-537, W-532S/E/N: 13:13-17:28; hazard areas: 13:15-17:57	191	based on launch on 02/11/2013
10:00	15:00	Wallops	VA	Orbital Sciences Antares	W-386, W-72A/B, & hazard areas: 14:53-16:23	110	based on launch on 07/13/2014
11:45	18:45	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 18:35-19:05	0	assume 10min before, 20min after launch based on SME input
15:23	23:23	Pacific Ocean	N/A	SpaceX Dragon Reentry	hazard area: 23:03-23:30	135	based on Dragon reentry on March 26, 2013
Day 3 – High SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes**
6:30	11:30	Titusville	FL	Virgin Galactic SpaceShip 2	hazard area: 11:20-11:50	50	assume 10min before, 20min after launch based on SME input
8:20	14:20	Van Horn	TX	Blue Origin PM2	hazard area: 14:10-14:40	0	assume 10min before, 20min after launch based on SME input
11:10	16:10	Cecil Field	FL	XCOR Lynx	hazard area: 16:00-16:30	180	assume 10min before, 20min after launch based on SME input
11:45	18:45	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 18:35-19:05	0	assume 10min before, 20min after launch based on SME input
12:00	19:00	White Sands Missile Range	NM	Sounding Rocket	R-5107H & R-5107E: 18:00-21:00	0	airspace based on 07/22/2014 launch at WSMR; timing based on single launch from Wallops on 07/20/2012 and confirmed by SME
13:50	19:50	Midland	TX	XCOR Lynx	hazard area: 19:40-20:10	0	assume 10min before, 20min after launch based on SME input
16:45	23:45	Front Range	CO	XCOR Lynx	hazard area: 23:35-00:05	150	assume 10min before, 20min after launch based on SME input

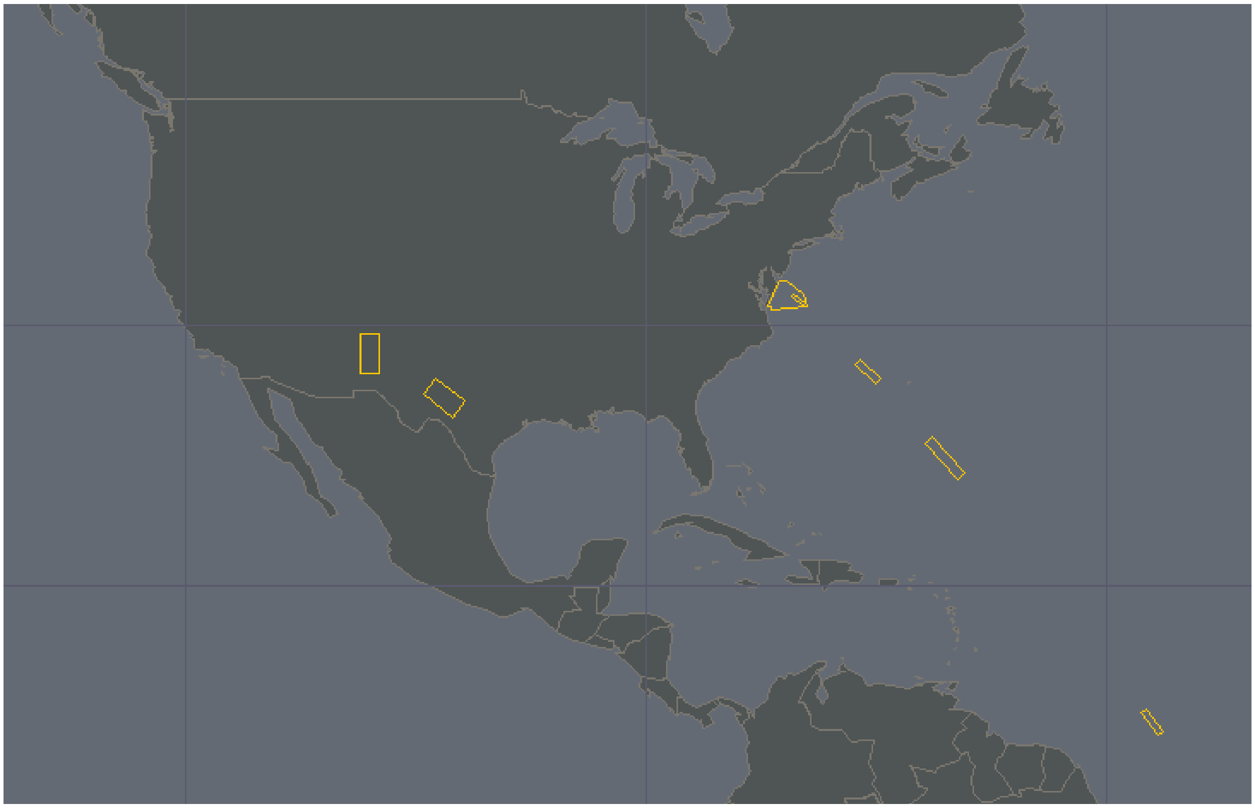

Figure 15. Closed Airspaces in the Current Day 1 Simulation Scenario

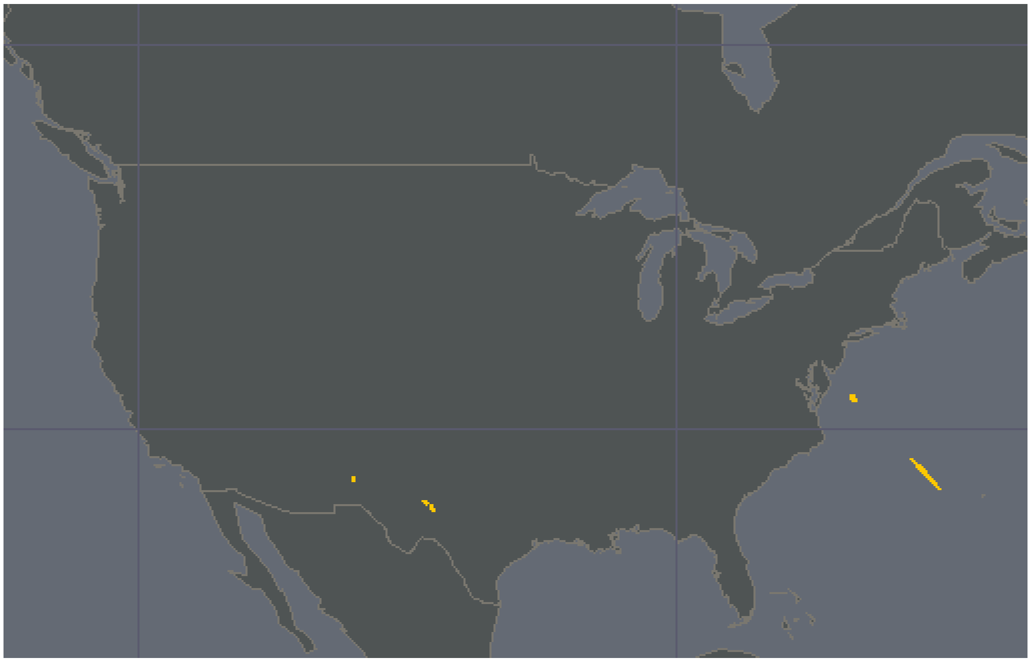

Figure 16. Closed Airspaces in the 4DE Day 1 Simulation Scenario

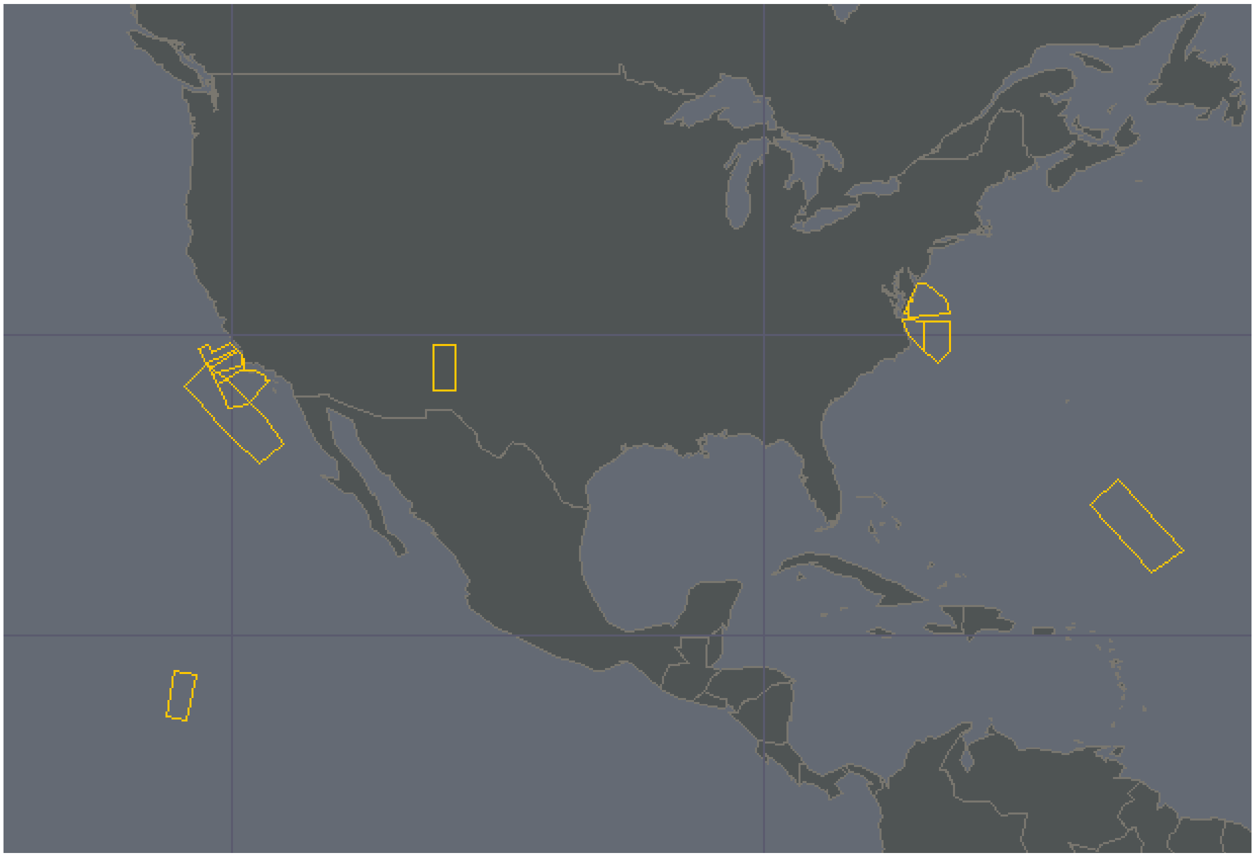

Figure 17. Closed Airspaces in the Current Day 2 Simulation Scenario

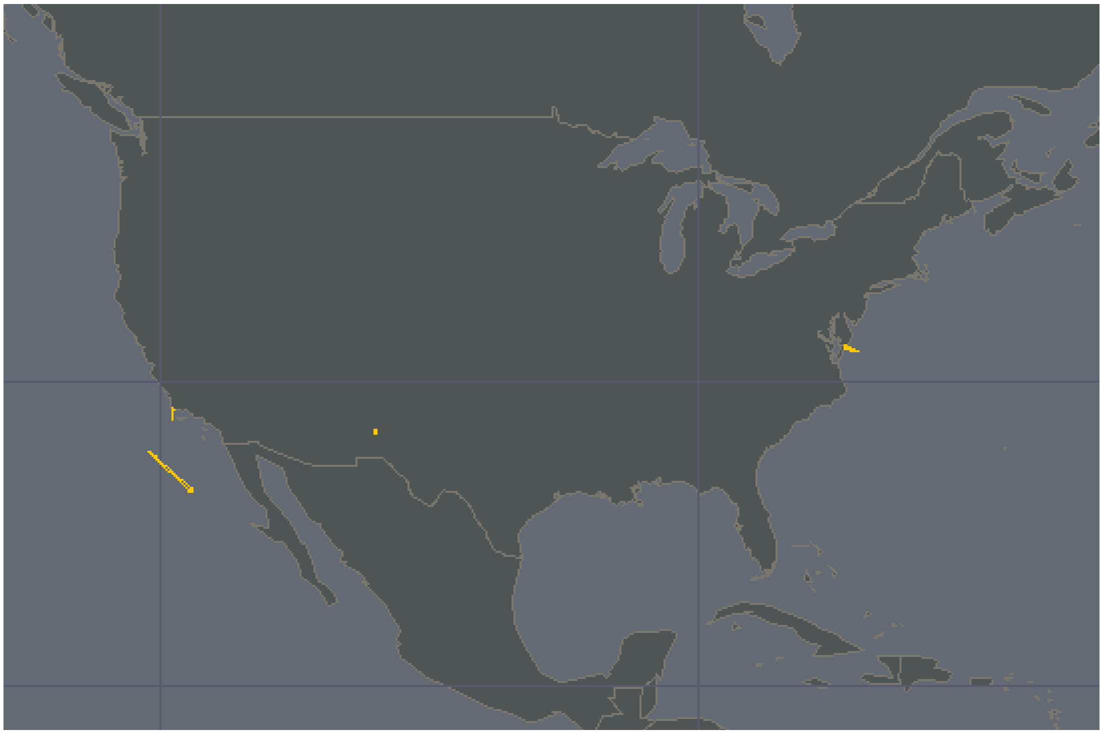

Figure 18. Closed Airspaces in the 4DE Day 2 Simulation Scenario

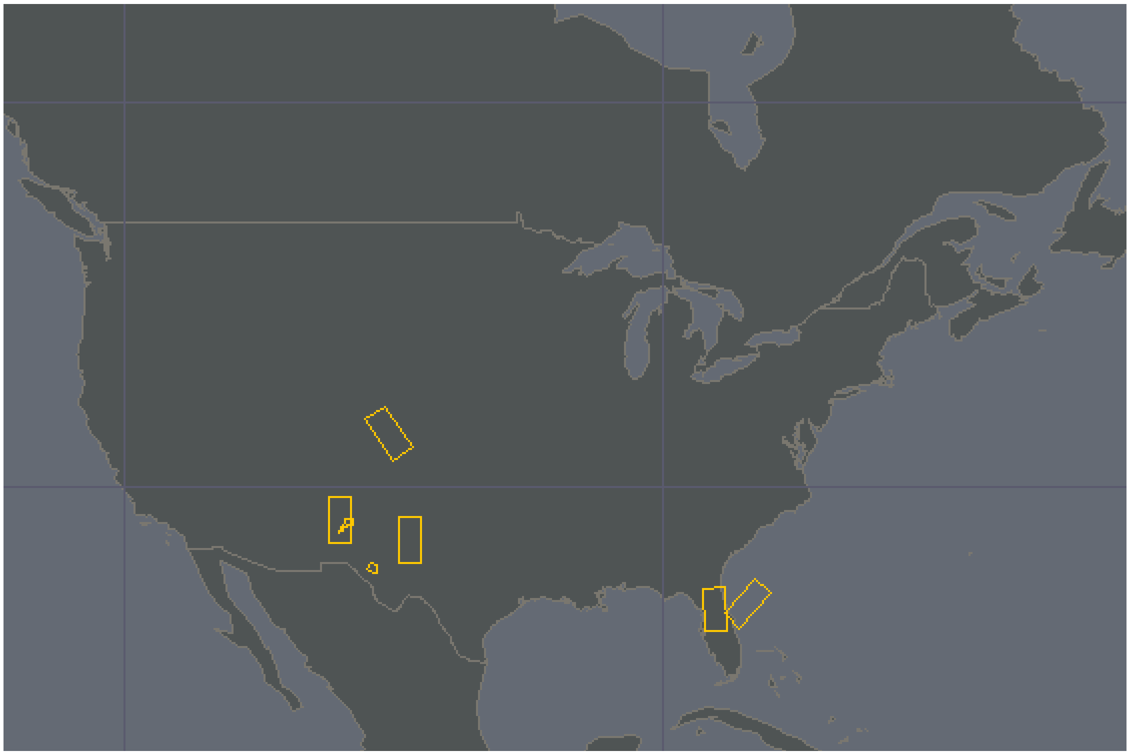

Figure 19. Closed Airspaces in the Current Day 3 Simulation Scenario

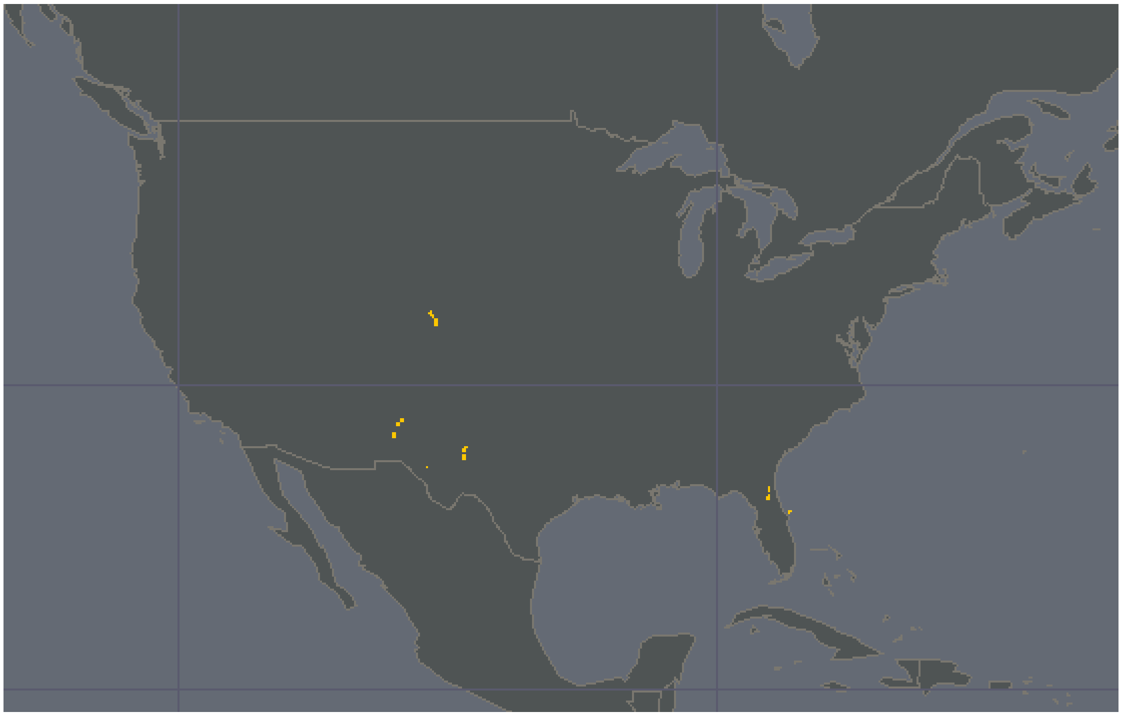

Figure 20. Closed Airspaces in the 4DE Day 3 Simulation Scenario

Table 13. SV Operations in 2025 Simulation Scenarios

2025 Scenarios							
Day 4 – Low SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes**
7:45	13:45	Midland	TX	XCOR Lynx	hazard area: 13:35-14:05	120	assume 10min before, 20min after launch based on SME input
8:10	15:10	Spaceport America	NM	Armadillo STIG-B	hazard areas: 12:55-16:55	0	airspace based on launch on 01/28/2012; timing based on SME input
9:18	14:18	Cecil Field	FL	XCOR Lynx	hazard area: 14:08-14:38	180	assume 10min before, 20min after launch based on SME input
10:35	18:35	Mojave	CA	XCOR Lynx	hazard area: 18:25-18:55	50	assume 10min before, 20min after launch based on SME input
12:30	21:30	Poker Flat	AK	Sounding Rocket	hazard areas: 14:20-24:20	23	based on aurora viewing mission launched on 03/03/2014
13:20	20:20	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 20:10-20:40	0	assume 10min before, 20min after launch based on SME input
Day 5 – Medium SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes**
9:00	16:00	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 15:50-16:20	0	assume 10min before, 20min after launch based on SME input
10:10	18:10	Vandenburg Air Force Base	CA	SpaceX Falcon 9	W-537, W-289N/S, W-532S, W-292W, R-2534A/B: 17:55-21:40; hazard areas: 18:10-21:40	180	based on launch from VAFB on 09/29/2013
10:18	16:18	Ellington Field	TX	generic capsule	hazard area: 15:58-16:28	315	assume 20min before, 10min after reentry based on SME input
10:35	18:35	Mojave	CA	XCOR Lynx	hazard area: 18:25-18:55	50	assume 10min before, 20min after launch based on SME input
13:45	20:45	Front Range	CO	Virgin Galactic SpaceShip 2	hazard area: 20:35-21:05	150	assume 10min before, 20min after launch based on SME input
14:00	21:00	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 20:50-21:20	0	assume 10min before, 20min after launch based on SME input
15:00	22:00	White Sands Missile Range	NM	Sounding Rocket	R-5107H & R-5107E: 21:00-00:00	0	airspace based on 07/22/2014 launch at WSMR; timing based on single launch from Wallops on 07/20/2012 and confirmed by SME
16:35	22:35	Midland	TX	XCOR Lynx	hazard area: 22:25-22:55	0	assume 10min before, 20min after launch based on SME input

2025 Scenarios							
Day 6 – High SV Operations							
Time (Local)	**Time (UTC)**	**Locations**	**State**	**Space Vehicle**	**Timing of Airspace Closure (UTC)**	**Azimuth**	**Notes**
2:00	11:00	Kodiak	AK	Orbital Sciences Minotaur	hazard areas: 10:40-11:55	130	assume 20min before, 1hr 15min total
7:00	15:00	Vandenburg Air Force Base	CA	Orbital Sciences Pegasus	W-283, W-285A, W-532N, & hazard areas: 14:45-15:27	196	based on Pegasus launch from VAFB on 06/27/2013
8:30	15:30	Front Range	CO	XCOR Lynx	hazard area: 15:20-15:50	150	assume 10min before, 20min after launch based on SME input
9:00	16:00	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 15:50-16:20	0	assume 10min before, 20min after launch based on SME input
9:45	14:45	Spaceport Georgia	GA	SpaceX Falcon 9	TFR: 14:15-15:18; hazard areas: 14:45-15:18	120	based on NOTAM for launch at Cape Canaveral on 03/01/2013
10:35	18:35	Mojave	CA	XCOR Lynx	hazard area: 18:25-18:55	50	assume 10min before, 20min after launch based on SME input
10:50	16:50	Van Horn	TX	Blue Origin PM2	hazard area: 16:40-17:10	0	assume 10min before, 20min after launch based on SME input
11:05	16:05	Titusville	FL	Virgin Galactic SpaceShip 2	hazard area: 15:55-16:25	50	assume 10min before, 20min after launch based on SME input
11:45	18:45	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 18:35-19:05	0	assume 10min before, 20min after launch based on SME input
11:50	17:50	Midland	TX	XCOR Lynx	hazard area: 17:40-18:10	120	assume 10min before, 20min after launch based on SME input
13:20	19:20	Ellington Field	TX	Virgin Galactic SpaceShip 2	hazard area: 19:10-19:40	120	assume 10min before, 20min after launch based on SME input
14:00	21:00	Spaceport America	NM	Virgin Galactic SpaceShip 2	hazard area: 20:50-21:20	0	assume 10min before, 20min after launch based on SME input
15:00	1:00	Spaceport Hawaii	HI	XCOR Lynx	hazard area: 00:50-01:20	200	assume 10min before, 20min after launch based on SME input
19:15	0:15	Cape Canaveral	FL	SpaceX Falcon 9	TFR: 23:45-00:48; hazard areas: 00:15-00:48	43	based on NOTAM for launch on 03/01/2013
20:20	2:20	Oklahoma Spaceport	OK	XCOR Lynx	hazard area: 02:10-02:40	315	assume 10min before, 20min after launch based on SME input

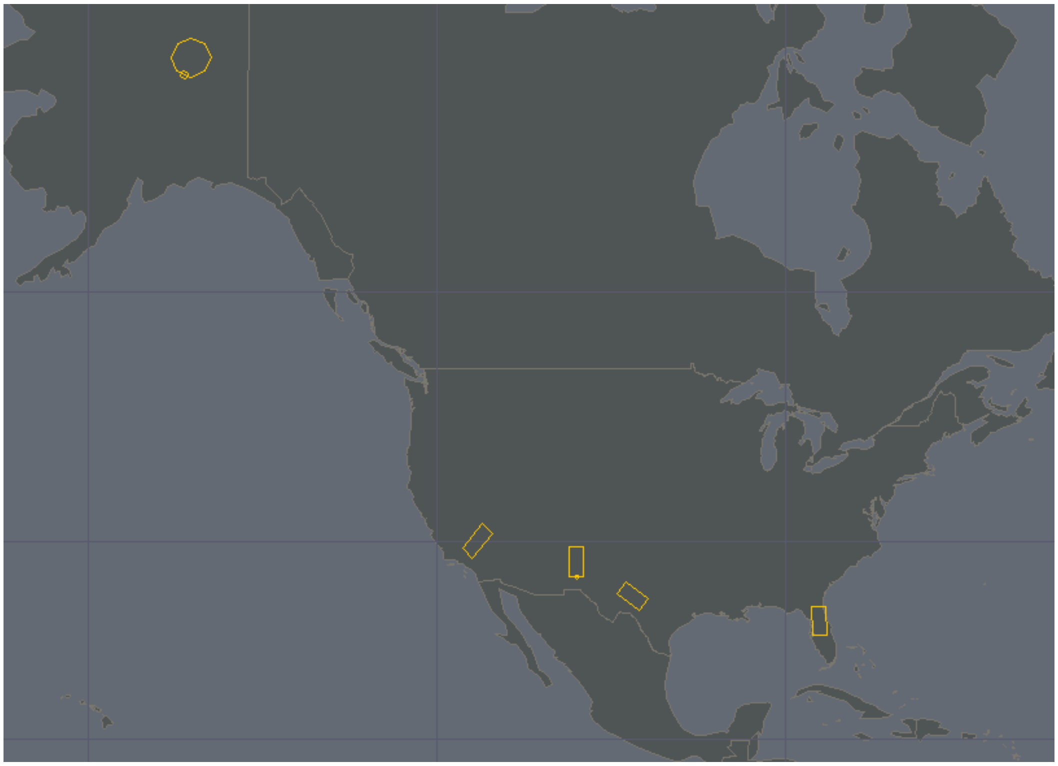

Figure 21. Closed Airspaces in the Current Day 4 Simulation Scenario

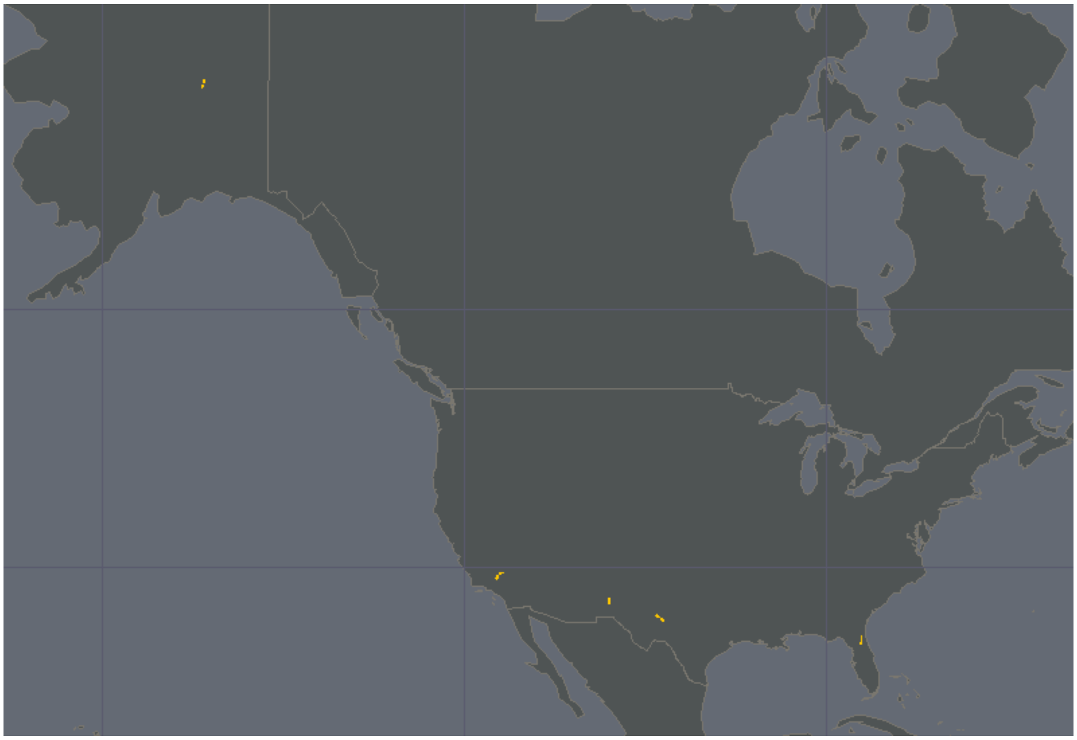

Figure 22. Closed Airspaces in the 4DE Day 4 Simulation Scenario

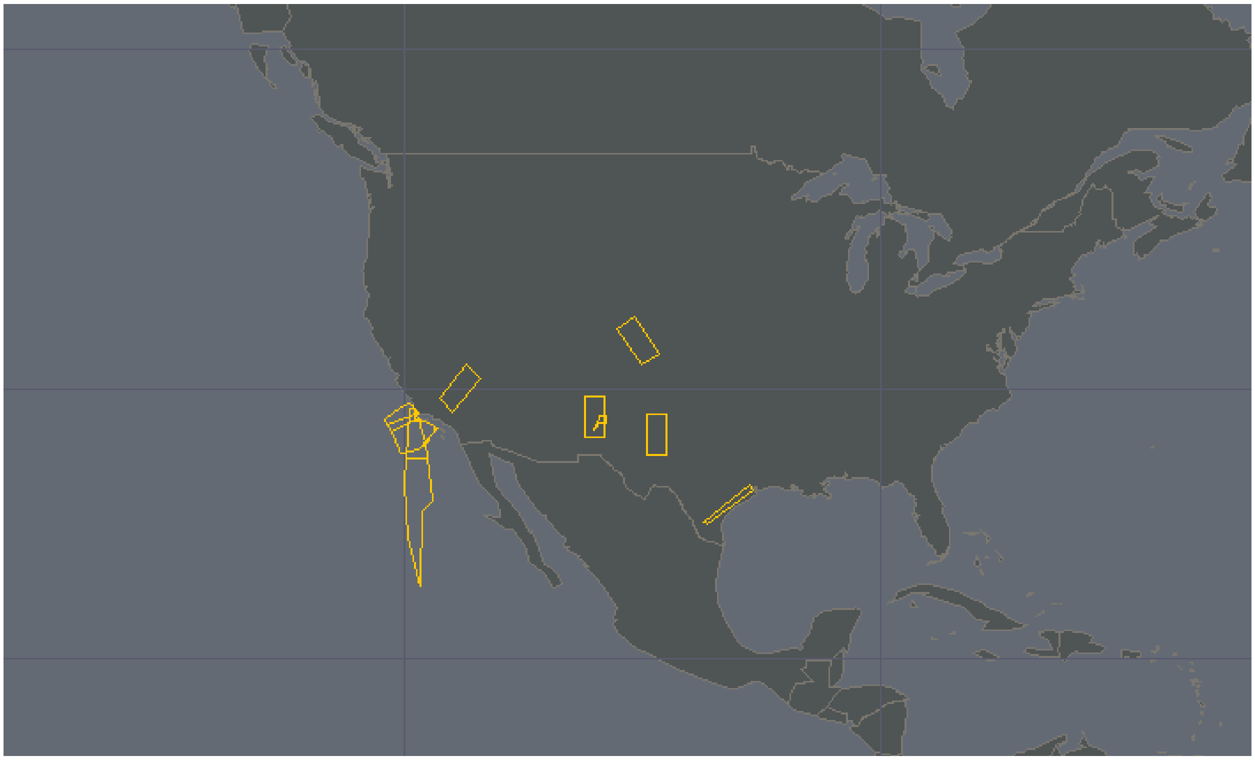

Figure 23. Closed Airspaces in the Current Day 5 Simulation Scenario

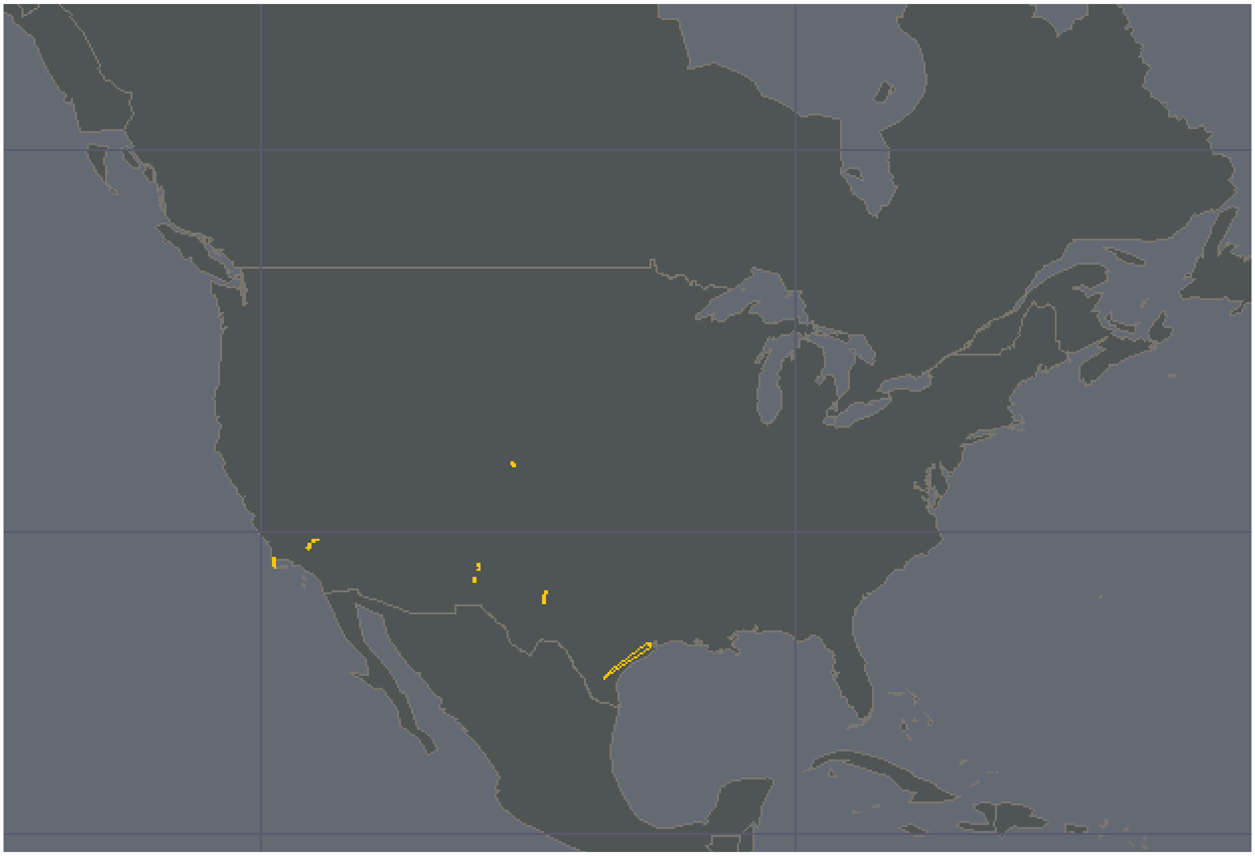

Figure 24. Closed Airspaces in the 4DE Day 5 Simulation Scenario

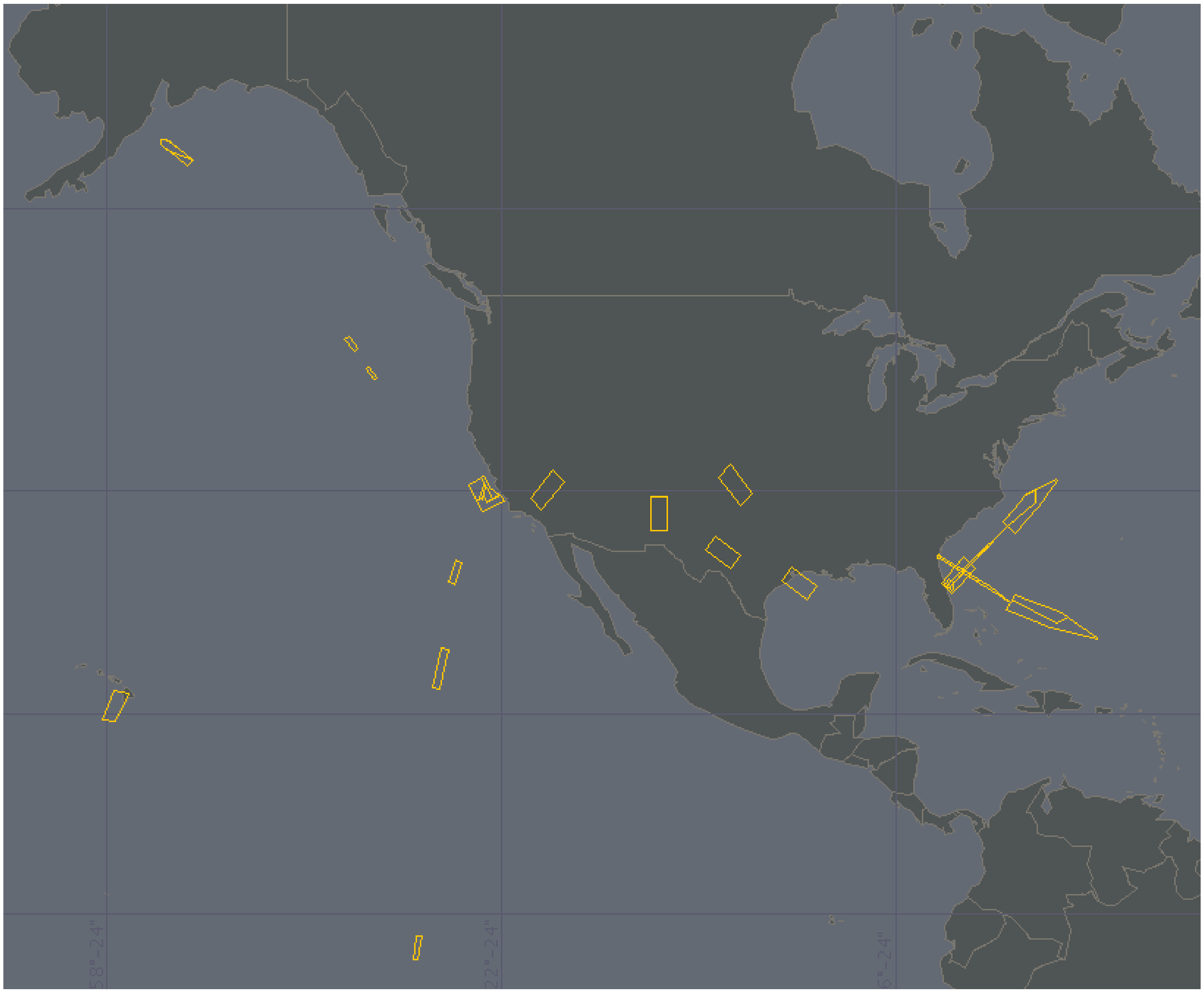

Figure 25. Closed Airspaces in the Current Day 6 Simulation Scenario

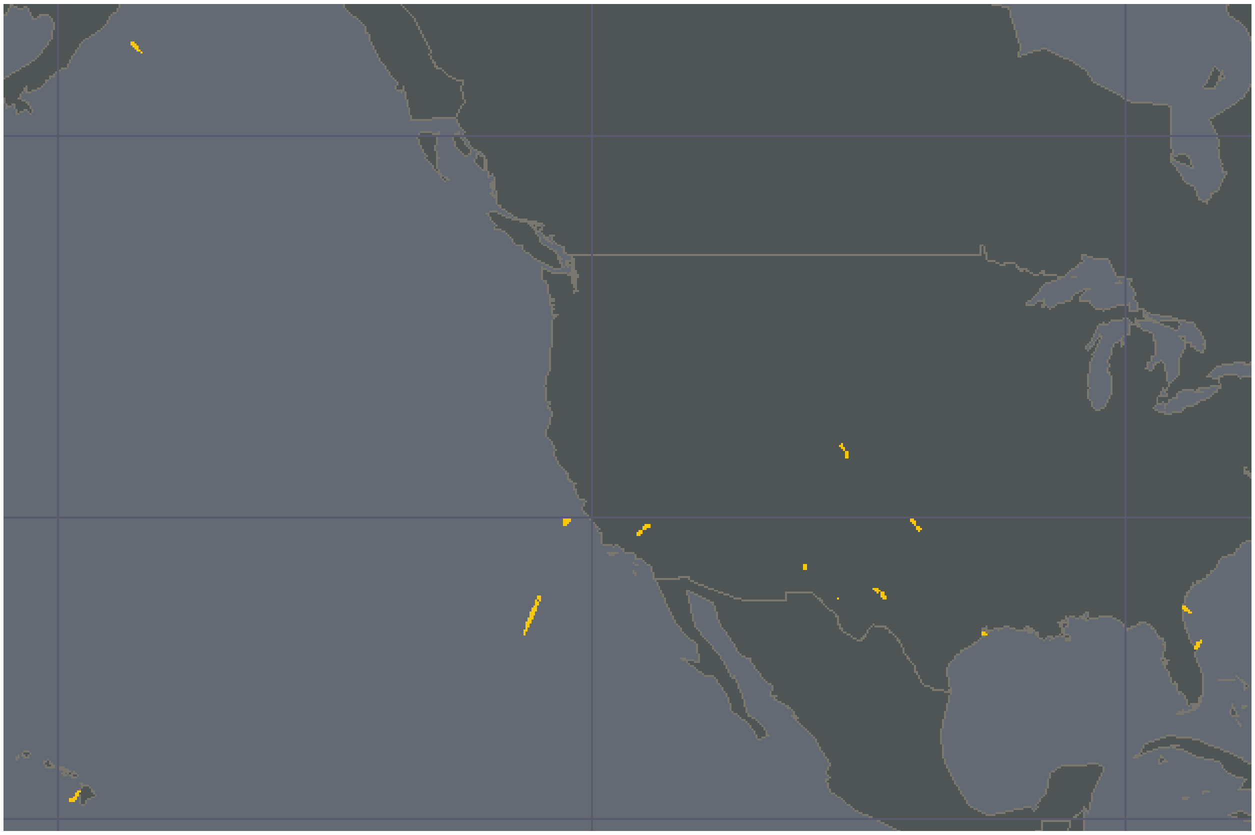

Figure 26. Closed Airspaces in the 4DE Day 6 Simulation Scenario

Appendix C: Summary of Flight-SAA Interactions

This appendix summarizes interaction counts for the six simulation days of the Current and 4DE scenarios. Note that each value is a count of unique flight and airspace interactions for a given scenario that includes both flights that were successfully rerouted and those that AirTOp failed to reroute. No flights interacted with the closed airspaces in the 4DE scenarios for Days 1 and 2.

Table 14. Flight and SAA Interactions for Current Day 1 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
LYNX_MIDLAND_2018L	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Midland, TX)	63
SS2_SPACEPORTAMERICA_2018L	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	56
W-386_PEGASUS_2018L	Current Day Procedure SAA for Orbital Science Pegasus Orbital Operation (Wallops Island, VA)	22
	Total	**141**

Table 15. Flight and SAA Interactions for Current Day 2 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
PACIFIC_REENTRY_2018M	Current Day Procedure SAA for a Pacific Ocean Reentry/Recovery Operation	3
ANTARES_ZDC2_2018M	Current Day Procedure SAA for Orbital Sciences Antares Orbital Operation (Mid-Atlantic Regional Spaceport/Wallops Island, VA)	1
ANTARES_ZNY1_2018M		1
W-386_ANTARES_2018M		37
W-289S_FALCON9_VAFB_2025M	Current Day Procedure SAA for Space X Falcon 9 Orbital Operation (Vandenberg AFB, CA)	5
W-532S_FALCON9_VAFB_2025M		2
W-537_FALCON9_VAFB_2025M		1
W-289S_ATLAS_VAFB_2018M	Current Day Procedure SAA for United Launch Alliance Atlas V Operation (Vandenberg AFB, CA)	40
W-532E_ATLAS_VAFB_2018M		16
W-532N_ATLAS_VAFB_2018M		16
W-532S_ATLAS_VAFB_2018M		22
W-537_ATLAS_VAFB_2018M		31
SS2_SPACEPORTAMERICA_2018M	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	42
	Total	**217**

Table 16. Flight and SAA Interactions for Current Day 3 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
LYNX_CECILFIELD_2018H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Cecil Field, FL)	221
LYNX_FRONTRANGE_2018H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Front Range/Spaceport Colorado, CO)	134
LYNX_MIDLAND_2018H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Midland, TX)	44
R-5107E_2018H	Current Day Procedure SAA for Sound Rocket Suborbital Operation (White Sands Missile Range, NM)	2
SS2_SPACEPORTAMERICA_2018H	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	42
SS2_TITUSVILLE_2018H	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Titusville, FL)	29
VANHORN_BLUEORIGIN1_2018H	Current Day Procedure SAA for Blue Origin PM2 Suborbital Operation (Van Horn, TX)	8
	Total	**480**

Table 17. Flight and SAA Interactions for 4DE Day 3 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
S4DE_LYNXFRONTRANGE_2018H7_2	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Front Range/Spaceport Colorado, CO)	1
S4DE_LYNXMIDLAND_2018H1_2	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Midland, TX)	1
	Total	**2**

Table 18. Flight and SAA Interactions for Current Day 4 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
LYNX_CECILFIELD_2025L	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Cecil Field, FL)	230
LYNX_MOJAVE_2025L	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Mojave, CA)	44
POKERFLAT_SOUNDINGROCKET_1_2025L	Current Day Procedure SAA for Sounding Rocket Suborbital Operation (Poker Flat, AK)	23
POKERFLAT_SOUNDINGROCKET_2_2025L		35
SS2_SPACEPORTAMERICA_2025L	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	53
	Total	**385**

Table 19. Flight and SAA Interactions for 4DE Day 4 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
S4DE_LYNXMIDLAND_2025L0_0	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Midland, TX)	1
S4DE_LYNXMIDLAND_2025L2_2		1
S4DE_SROCKETPOKERFLAT_2025L12_0	Stanford 4D Compact Envelope for Sounding Rocket Suborbital Operation (Poker Flat, AK)	1
	Total	**3**

Table 20. Flight and SAA Interactions for Current Day 5 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
ELLINGTONFIELD_CONTRECOVERY_2025M	Current Day Procedure SAA for a Continental Reentry/Recovery Operation (Ellington Field, TX)	48
LYNX_MIDLAND_2025M	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Midland, TX)	37
LYNX_MOJAVE_2025M	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Mojave, CA)	45
R-2534A_FALCON9_VAFB_2025M	Current Day Procedure SAA for Space X Falcon 9 Orbital Operation (Vandenberg AFB, CA)	12
R-2534B_FALCON9_VAFB_2025M		7
SS2_FRONTRANGE_2025M	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Front Range/Spaceport Colorado, CO)	172
SS2_SPACEPORTAMERICA_2025M_A	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	64
SS2_SPACEPORTAMERICA_2025M_B	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	43
VAFB_FALCON9_1_2025M	Current Day Procedure SAA for Space X Falcon 9 Orbital Operation (Vandenberg AFB, CA)	31
VAFB_FALCON9_2_2025M		4
W-289S_FALCON9_VAFB_2025M		29
W-292W_FALCON9_VAFB_2025M		2
W-532S_FALCON9_VAFB_2025M		22
W-537_FALCON9_VAFB_2025M		12
	Total	**528**

Table 21. Flight and SAA Interactions for 4DE Day 5 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
S4DE_REENTRYELLFIELD_2025M6_0	Stanford 4D Compact Envelope for a Continental Reentry/Recovery Operation (Ellington Field, TX)	4
	Total	**4**

Table 22. Flight and SAA Interactions for Current Day 6 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
CAPEC_FALCON9_TFR_2025H	Current Day Procedure SAA for Space X Falcon 9 Orbital Operation (Cape Canaveral, FL)	24
CAPEC_FALCON91_2025H		19
CAPEC_FALCON92_2025H		2
CAPEC_FALCON93_2025H		8
LYNX_FRONTRANGE_2025H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Front Range/Spaceport Colorado, CO)	143
LYNX_HAWAII_2025H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Spaceport Hawaii, HI)	5
LYNX_MIDLAND_2025H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Midland, TX)	59
LYNX_MOJAVE_2025H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Mojave, CA)	44
LYNX_OKLAHOMA_2025H	Current Day Procedure SAA for XCOR Lynx Suborbital Operation (Spaceport Oklahoma, OK)	28
SPACEPORTGA_FALCON9_TFR_2025H	Current Day Procedure SAA for Space X Falcon 9 Orbital Operation (Spaceport Georgia, GA)	86
SPACEPORTGA_FALCON91_2025H		59
SPACEPORTGA_FALCON92_2025H		15
SPACEPORTGA_FALCON93_2025H		25
SS2_ELLINGTONFIELD_2025H	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Ellington Field, TX)	48
SS2_SPACEPORTAMERICA_2025H_A	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	64
SS2_SPACEPORTAMERICA_2025H_B	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	47
SS2_SPACEPORTAMERICA_2025H_C	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Spaceport America, NM)	43
SS2_TITUSVILLE_2025H	Current Day Procedure SAA for Virgin Galactic Spaceship 2 Suborbital Operation (Titusville, FL)	68
VAFB_PEGASUS2_2025H	Current Day Procedure SAA for Orbital Science Pegasus Orbital Operation (Vandenberg AFB, CA)	2
VANHORN_BLUEORIGIN1_2025H	Current Day Procedure SAA for Blue Origin PM2 Suborbital Operation (Van	25

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
	Horn, TX)	
W-532N_PEGASUS_VAFB_2025H	Current Day Procedure SAA for Orbital Science Pegasus Orbital Operation (Vandenberg AFB, CA)	1
	Total	**815**

Table 23. Flight and SAA Interactions for 4DE Day 6 Simulation Scenario

Special Activity Airspace (SAA) ID	SAA Description	Count of Unique Flight-SAA Interactions
S4DE_BLUEORIGIN_2025H0_2	Stanford 4D Compact Envelope for Blue Origin PM2 Suborbital Operation (Van Horn, TX)	2
S4DE_FALCON9GA_2025H0_1	Stanford 4D Compact Envelope for Space X Falcon 9 Orbital Operation (Spaceport Georgia, GA)	1
S4DE_FALCON9GA_2025H1_1		1
S4DE_FALCON9GA_2025H1_2		1
S4DE_LYNXFRONTRANGE_2025H0_0	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Front Range/Spaceport Colorado, CO)	1
S4DE_LYNXFRONTRANGE_2025H1_0		2
S4DE_LYNXHAWAII_2025H1_0	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Spaceport Hawaii, HI)	1
S4DE_LYNXOK_2025H7_2	Stanford 4D Compact Envelope for XCOR Lynx Suborbital Operation (Spaceport Oklahoma, OK)	1
	Total	**10**

Appendix D: MAP Threshold Violations by Sector

The number of MAP threshold violations was counted for the Baseline, Current and 4DE simulation scenarios, and any variation in these counts between scenarios are reported in Table 24 and Table 25. Sectors whose maximum occupancy exceeded the MAP threshold the same amount of times in all scenarios were not included in these tables. Cells highlighted purple indicate increases in violations as compared to the baseline scenario, and those highlighted green indicate a decrease from the baseline.

Table 24. Change in Number of MAP Threshold Violations in 2018 Simulation Scenarios

Center	Sector ID	2018 Baseline	2018 Low Current	2018 Low 4DE	2018 Med Current	2018 Med 4DE	2018 High Current	2018 High 4DE
ZAB	ZAB058	6	7	6	6	6	6	6
ZAB	ZAB067	20	21	20	20	20	20	20
ZAB	ZAB070	0	2	0	0	0	0	0
ZDC	ZDC012	4	4	4	4	4	5	4
ZDC	ZDC016	20	20	20	20	20	19	20
ZDV	ZDV014	6	6	6	6	6	7	6
ZDV	ZDV034	3	3	3	3	3	4	3
ZHU	ZHU074	1	0	1	1	1	1	1
ZHU	ZHU078	1	3	1	1	1	1	1
ZLA	ZLA028	2	2	2	1	2	2	2
ZMA	ZMA018	0	0	0	0	0	1	0
ZMA	ZMA025	11	11	11	11	11	14	11
ZME	ZME020	5	5	5	5	5	4	5
ZMP	ZMP017	1	1	1	1	1	2	1
ZMP	ZMP042	1	1	1	1	1	2	1
ZOA	ZOA014	0	0	0	1	0	0	0
ZTL	ZTL002	19	19	19	19	19	18	19
ZTL	ZTL034	11	11	11	11	11	12	11

Table 25. Change in Number of MAP Threshold Violations in 2025 Simulation Scenarios

Center	Sector ID	2025 Baseline	2025 Low Current	2025 Low 4DE	2025 Med Current	2025 Med 4DE	2025 High Current	2025 High 4DE
ZAB	ZAB050	9	9	9	8	9	9	9
ZAB	ZAB058	14	13	14	11	14	11	14
ZAB	ZAB067	29	31	29	29	29	29	29
ZAB	ZAB070	1	3	1	5	1	4	1
ZAB	ZAB072	1	2	1	1	1	1	1
ZAB	ZAB080	18	17	18	18	18	18	18
ZAB	ZAB091	5	5	5	5	5	4	5
ZAB	ZAB092	5	6	5	5	5	5	5
ZAB	ZAB098	1	1	1	2	1	2	1
ZAU	ZAU023	6	5	6	6	6	6	6
ZAU	ZAU047	4	5	4	4	4	4	4
ZBW	ZBW020	37	36	37	37	37	37	37
ZBW	ZBW046	35	36	35	35	35	35	35
ZDC	ZDC012	7	7	7	7	7	9	7
ZDC	ZDC016	30	29	30	30	30	30	30
ZDC	ZDC019	2	2	2	2	2	3	2
ZDC	ZDC036	17	17	17	17	17	16	17
ZDC	ZDC050	15	15	15	15	15	14	15
ZDV	ZDV004	1	1	1	1	1	0	1
ZDV	ZDV009	0	0	0	1	0	0	0
ZDV	ZDV016	0	0	0	3	0	1	0
ZDV	ZDV031	2	3	2	2	2	2	2
ZDV	ZDV033	8	8	8	9	8	8	8
ZDV	ZDV039	1	1	1	1	1	0	1
ZFW	ZFW089	6	6	6	6	6	7	6
ZHU	ZHU046	7	7	7	7	7	8	7
ZHU	ZHU065	1	1	1	1	1	2	1
ZHU	ZHU070	7	7	7	6	7	7	7
ZHU	ZHU079	7	7	7	7	7	8	7
ZHU	ZHU082	3	3	3	2	3	3	3
ZHU	ZHU083	1	0	1	1	1	1	1
ZHU	ZHU097	14	13	14	14	14	14	14
ZID	ZID091	6	6	6	6	6	7	6
ZID	ZID093	1	0	1	1	1	1	1
ZJX	ZJX049	8	8	8	8	8	10	8
ZJX	ZJX050	2	2	2	2	2	3	2
ZJX	ZJX058	1	3	1	1	1	0	1
ZJX	ZJX065	5	5	5	5	5	4	5

Center	Sector ID	2025 Baseline	2025 Low Current	2025 Low 4DE	2025 Med Current	2025 Med 4DE	2025 High Current	2025 High 4DE
ZJX	ZJX068	1	1	1	1	1	0	1
ZJX	ZJX076	10	10	10	10	10	11	10
ZKC	ZKC092	2	3	2	3	2	2	2
ZKC	ZKC094	3	3	3	2	3	3	3
ZLA	ZLA016	8	7	8	6	8	6	8
ZLA	ZLA018	0	0	0	1	0	1	0
ZLA	ZLA025	0	0	0	2	0	0	0
ZLA	ZLA030	14	15	14	14	14	14	14
ZLA	ZLA032	26	25	26	26	26	26	26
ZLA	ZLA036	25	26	25	24	25	25	25
ZLA	ZLA037	16	16	16	16	16	15	16
ZLA	ZLA039	20	20	20	20	20	19	20
ZLC	ZLC004	7	6	7	7	7	7	7
ZLC	ZLC020	2	3	2	2	2	2	2
ZMA	ZMA059	0	0	0	0	0	2	0
ZMA	ZMA060	15	14	15	15	15	15	15
ZMA	ZMA063	0	0	0	0	0	3	0
ZME	ZME020	12	12	12	12	12	13	12
ZMP	ZMP040	0	1	0	0	0	0	0
ZMP	ZMP042	4	4	4	5	4	4	4
ZNY	ZNY010	2	2	2	1	2	1	2
ZNY	ZNY066	2	2	2	2	2	1	2
ZNY	ZNY068	3	4	3	3	3	3	3
ZOA	ZOA014	1	1	1	1	1	2	1
ZOA	ZOA033	3	5	3	3	3	3	3
ZOA	ZOA036	6	5	6	6	6	6	6
ZOB	ZOB059	0	1	0	0	0	0	0
ZOB	ZOB069	4	4	4	3	4	4	4
ZSE	ZSE048	0	1	0	0	0	0	0
ZTL	ZTL006	6	6	6	6	6	4	6
ZTL	ZTL008	13	14	13	13	13	13	13
ZTL	ZTL010	4	4	4	5	4	4	4
ZTL	ZTL031	6	7	6	6	6	6	6
ZTL	ZTL039	5	4	5	4	5	5	5
ZTL	ZTL040	5	4	5	5	5	5	5
ZTL	ZTL042	12	11	12	12	12	12	12
ZTL	ZTL050	21	22	21	21	21	21	21