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ABSTRACT

The growth in launch and reentry operations in the National Airspace System (NAS) presents the Federal Aviation Administration (FAA) with the challenge of integrating them more efficiently while also minimizing effects on other NAS users and maintaining safety. Currently, to maintain safety and account for unforeseen events such as vehicle breakup, the FAA segregates large amounts of airspace, called Aircraft Hazard Areas (AHAs), from traditional NAS users during launch and reentry operations. In order to minimize effects on NAS users, some AHAs during reentry are dynamically activated only if an unexpected event occurs. If a dynamic AHA is activated, then aircraft would have to evacuate from the AHA before debris reaches the controller's airspace (60,000 feet and below). The FAA can determine how long it takes for debris to reach the NAS, but it does not have a capability to statistically examine how long it would take aircraft to evacuate these AHAs while considering different aircraft performance parameters, airspace traffic patterns, and controllers with different response times. The FAA could also implement smaller AHAs for launches by using dynamic AHAs, but only if they can better understand the time needed to evacuate them. The MITRE Corporation's Center for Advanced Aviation System Development (MITRE CAASD) is developing a flexible, fast-time modeling and simulation capability that examines the time to evacuate these AHAs and quantifies how different factors (e.g., air traffic control notification delay, traffic orientation, and traffic density) affect those times. This paper describes this modeling capability and demonstrates potential use cases.

I. Introduction: Growth and Expansion of the Space Transportation Landscape

Space transportation and services are undergoing rapid expansion, commercialization, and development. New companies are envisioning operations that could occur daily with innovative vehicle designs that have not been seen before. These vehicles include reusable rocket stages that fly back to a landing site, air launches, spaceplanes, and high altitude balloons. Additionally, there are a growing number of commercial spaceports throughout the U.S., which provides more opportunities and locations to operate these vehicles. As the industry has modernized, so too must the Federal Aviation Administration's (FAA's) standards, regulations, and operations for handling air and space transportation in the National Airspace System (NAS). The FAA is faced with the challenge of integrating growing launch and re-entry operations while minimizing effects on other NAS users. Currently, these operations utilize Aircraft Hazard Areas (AHAs) to segregate large amounts of airspace in order to maintain safety. This practice requires other NAS users including military, general aviation, and commercial flight operations to reroute their operations around the AHAs or schedule their operations to avoid the timeframes of the AHAs. As these operations grow, this practice will result in Launch and Reentry Vehicle (LRV) operations having more noticeable and frequent effects on the NAS.

II. Using Dynamic AHAs for More Efficient Launch and Reentry Operations

The FAA is examining ways to minimizing the size and duration of AHAs for LRV operations. In order to improve efficiency, in some instances the FAA releases airspace as soon as launch vehicle has passed through it and then routes aircraft through it. For reentries, the FAA has allowed the airspace below the planned trajectory to remain open for regular operation rather than close it off, which would have greatly reduced NAS capacity. In the event of a debris event during re-entry, a new AHA would be generated based on the last known state vector of the re-entry vehicle and distributed to air traffic control (ATC) to clear the airspace and implement necessary traffic management initiatives (e.g., increased separation between aircraft and ground stops at underlying/affected airports). For future launches, the FAA is exploring the use of a new separation concept [1] during launch that employs much smaller AHAs during nominal operations ("the concept"), but a larger contingent AHA would not be activated during nominal operations. Hence, that contingent airspace would be available for NAS users to utilize. Portions of the contingent AHA would be activated only when an unforeseen event happens. This concept would be employed only for launch vehicles with operational histories that demonstrate low probability of failure (e.g., breakup, loss of control, loss of surveillance, etc.). This concept would also require a capability to quickly generate AHAs in real time and display them to controllers so traffic can be rerouted and evacuated.

Maximizing the amount of time controllers have to respond and minimizing the time to evacuate are critical to ensuring safety for these operations. MITRE has recognized this and is developing a capability to quantitatively evaluate the needed ATC response times for LRV operations, and examine the sensitivities that different factors have on the ATC response times when using dynamic AHAs. In particular, MITRE is able to provide quantitative studies on the response time or advanced notice needed for ATC to safely separate aircraft from unplanned re-entries and dynamic AHAs. It also allows the FAA to explore strategies for how ATC might respond to them.

III. Enabling More Efficient Operations: A Modeling Capability to Evaluate the Safety of Dynamic AHAs

The basis of the MITRE modeling framework is a Monte Carlo simulation tool, which has been used for several tasks in the past including evaluating Unmanned Aircraft System Sense and Avoid algorithms [2][3], En Route Automation and Modernization surveillance performance, and evaluating surveillance requirements for Automatic Dependent Surveillance – Broadcast (ADS-B) [4]. The research team adapted and enhanced it to evaluate space launch and re-entry operations through new ATC control algorithms, an updated surveillance model for LRV operations, safety metric calculations, and incorporating probabilistic ATC and pilot response times. Additionally, models for space vehicle trajectories and debris (leveraging prior debris modeling from Stanford University [5]) have been developed.

The Monte Carlo simulation capability is comprised of the following models and algorithms: aircraft model, ATC control algorithms (including a hazard volume evacuation algorithm, hazard-volume avoidance algorithm, and a LRV-aircraft separation algorithm), wind model, navigation sensor error model, controller workload model, and ADS-B model. These are depicted in Figure 3-1. The capability is still in development, thus all quantitative metrics generated should be deemed preliminary and will require further validation.

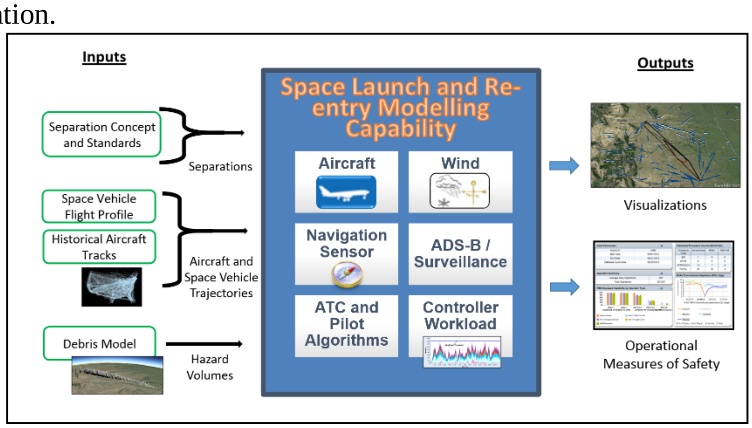

Figure 3-1. High-level depiction of MITRE modeling capability for LRV operations (source: MITRE).

The simulation inputs include nominal and off-nominal hazard volume boundaries, space vehicle trajectories (including trajectories for the stages), probabilistic response times for air traffic controllers and pilots, aircraft traffic density, and surveillance performance. Based on these inputs, Monte Carlo simulations are run to generate various operational measures of safety that can be used to examine the operational risks for each space launch and re-entry operation. The results can be analyzed to determine a required warning time to safely evacuate and avoid dynamic hazard volumes. It also outputs Google Earth files so that each scenario can be visualized. A more detailed description about the model and its components is described in [6].

IV. Potential Launch and Reentry Scenarios for Evaluation

Operational scenarios were used to demonstrate the modeling capability. Scenarios were derived from notional and historical launch and re-entry operations. The scenarios facilitate the measurement of metrics associated with ATC response times regarding clearing air traffic away from AHAs associated with nominal and off-nominal events. Peak traffic times were selected in order to simulate stress on modeling outputs. The ATC notification delay was varied (e.g. one minute, three minutes, five minutes) to assess its impact on response times. Scenario descriptions are included below.

Scenario #1 - Cape Canaveral Launch

This scenario describes the orbital launch of a rocket from Kennedy Space Center (KSC) in Florida (see Figure 4-2).

Figure 4-1. Vertical Rocket Launch from KSC (source: Wikipedia).

The scenario includes the use of a dynamic AHA for an off-nominal event. The rocket's trajectory from launch is eastbound over the Atlantic Ocean – crossing several heavily used commercial routes, military routes and flight operations areas. The sequence of events transpires as follows. At 15 minutes before launch (L-15) the planned Launch Danger Zone AHA and 1st Stage Reentry AHA are activated for the nominal launch activity (yellow polygons in Figure 4-2), and ATC reroutes aircraft outside of it for the launch. The Launch Danger Zone AHA is about 51 nautical miles (NM) by 6 NM and the 1st Stage Reentry AHA is about 86 NM by 55 NM. Normally, the AHA would remain active until 3 minutes after launch (L+3) and confirmation is obtained by ATC that the launch is nominal and the rocket has proceeded downrange. However, in this case a failure occurs with the rocket shortly after launch (T+2.5). Based on the trajectory, altitude, and speed, an Off-Nominal Failure AHA (red polygon in Figure 4-2) would be dynamically generated and communicated to ATC. The size of this AHA is about 64 NM by 26 NM. The Off-Nominal Failure AHA is active from L+ 2.5 to L+35. ATC evacuates the Off-Nominal Failure AHA and reroutes aircraft outside of it to avoid the AHA until debris are no longer a factor. Sample traffic data from that region is depicted as green lines in Figure 4-2. It is assumed that the Launch Danger Zone AHA and 1st Stage Reentry AHA are inactive when the Off-Nominal Failure AHA is Active.

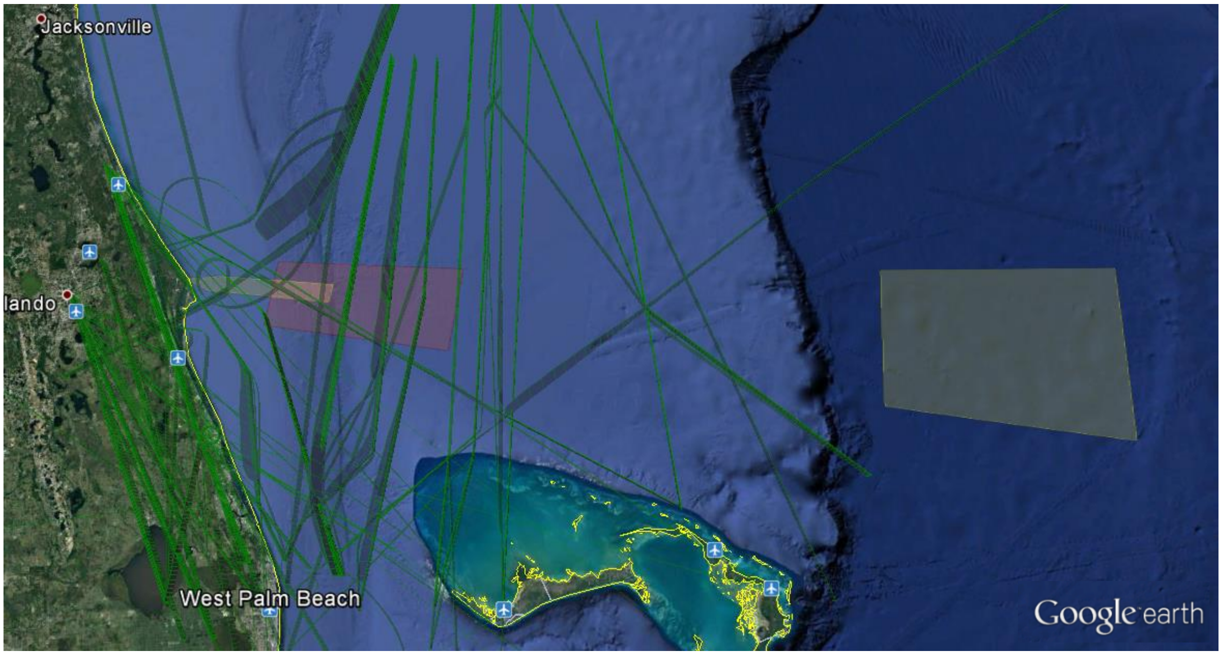

Figure 4-2. AHAs for Launch Danger Zone and 1st Stage Reentry (in yellow) and Off-Nominal Failure (in red) for Cape Canaveral launch with sample air traffic data in the region (green). The nominal AHAs are assumed inactive when the Off-Nominal Failure AHA is active (source: MITRE).

Scenario #2 – Southeast Texas Launch

This scenario describes the orbital launch of a rocket from a notional launch facility near southeast Texas. The notional rocket trajectory is eastbound from southeast Texas over the Gulf of Mexico, crossing several dense commercial flight routes in the Gulf. Figure 4-3 depicts the Launch Danger Zone AHA and the 1st Stage Reentry AHA as the two yellow polygons. The Launch Danger Zone AHA is about 83 NM by 10 NM, and the 1st Stage AHA is about 95 NM by 67 NM. A failure occurs with the rocket shortly after launch (T+2.5). Based on trajectory, altitude and speed, an Off-Nominal Failure AHA (red polygon in Figure 4-3) would be dynamically generated and communicated to ATC. The size of this AHA is about 63 NM by 48 NM. The Off-Nominal Failure AHA is active from L+ 2.5 to L+35. ATC evacuates the Off-Nominal Failure AHA and reroutes aircraft outside of it to avoid the AHA until debris are no longer a factor. Sample traffic from that region is depicted as green lines/aircraft in Figure 4-3. It is assumed that the Launch Danger Zone AHA and 1st Stage Reentry AHA are inactive when the Off-Nominal Failure AHA is Active.

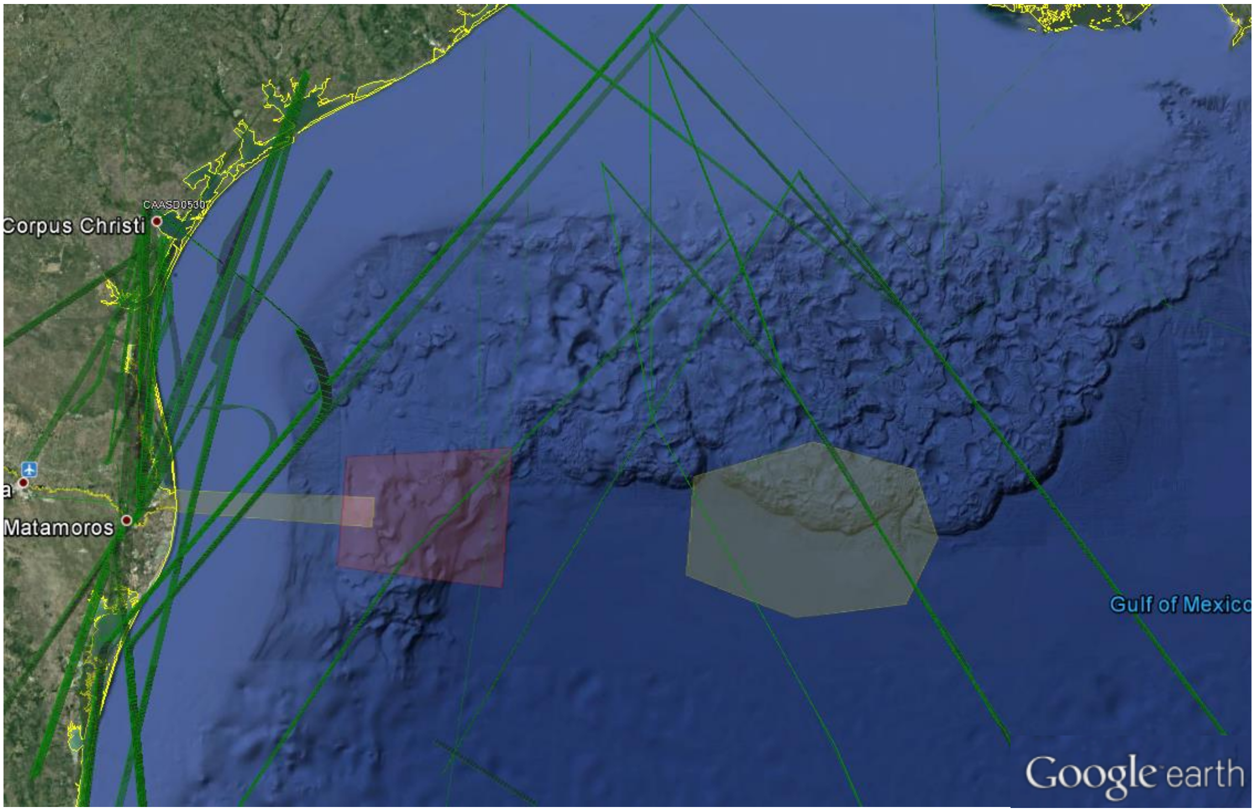

Figure 4-3. AHAs for Launch Danger Zone and 1st Stage Reentry (in yellow) and Off-Nominal Failure (in red) for Southeast Texas Launch with sample air traffic data in the region (green). The nominal AHAs are assumed inactive when the Off-Nominal Failure AHA is active (source: MITRE).

Scenario #3 – Capsule Re-entry

This scenario describes a capsule re-entering the earth's atmosphere and splashing down in the Pacific Ocean off the coast of Mexico. As part of the mission planning, hazard areas were planned for the Continental United States (CONUS) that involved AHAs that accounted for an off-nominal de-orbit burn for the capsule – which if a miscalculation or thruster malfunction would have occurred, it may have resulted in possible entry of the capsule into CONUS airspace. Although AHAs were calculated along the entire capsule trajectory (to factor an off-nominal deorbit burn) beyond the oceanic splash down target area, for modeling purposes, MITRE examined a single dynamic AHA that overlaid the central United States (see Figure 4-4). The dashed white line in the figure indicates the direction of the reentry coming from the southwest towards the northeast. The red lines indicate the boundaries of FAA Air Route Traffic Control Centers. This AHA is about 1,100 NM by 98 NM, and would be dynamically activated (along with several other off-nominal AHAs) in the event of an off-nominal burn event.

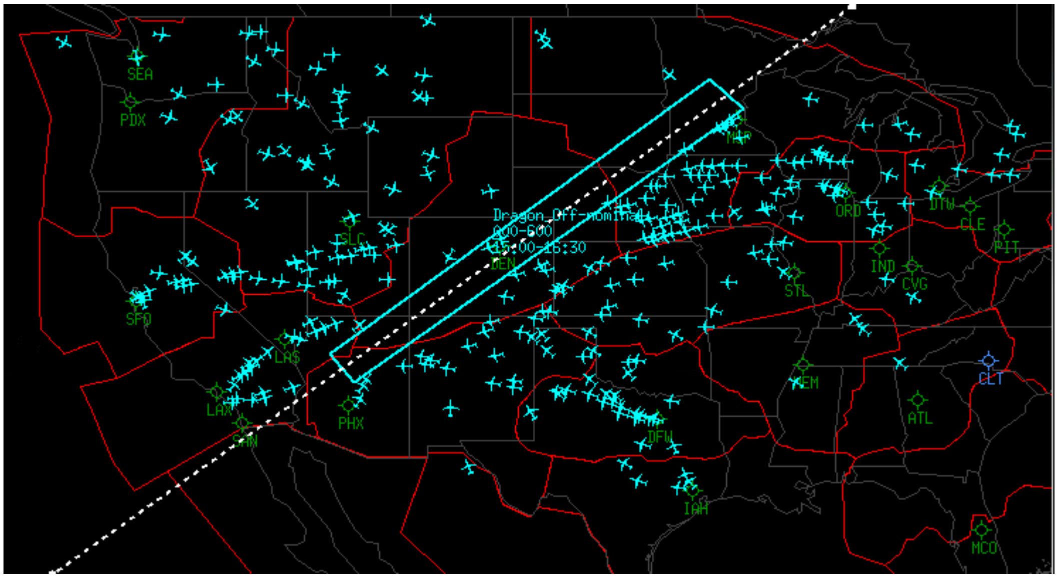

Figure 4-4. Single Off-Nominal Failure AHA for reentry capsule during de-orbit burn. The dashed line in the figure indicates the direction of the reentry coming from the southwest towards the northeast. The red lines are boundaries of FAA Air Route Traffic Control Centers (source: MITRE).

V. Simulation Results of Potential Scenarios

The simulation variables include the following factors: (1) ATC notification delay (one minute, three minutes, and five minutes), (2) traffic time of the day (morning, mid-day, and evening), and (3) traffic flow orientation (quantized to 30-degree bins). There are five iterations in each simulation. Each iteration in a simulation uses the same values for the factors.

The metrics examined in this analysis were (1) the time to clear the hazard area and (2) the time in the hazard area. For each iteration, the time to clear the hazard area measured how long it took for all aircraft to clear a dynamic AHA after it became active. Specifically, it measured the time between when the dynamic AHA became active and when the last aircraft exited, even if that aircraft entered the dynamic AHA after it became active. The time in the hazard area was measured for each aircraft that entered a dynamic AHA after it became active, or that was in it during activation. The MITRE modeling capability measured the time it took an aircraft in a dynamic AHA to exit it after it became active.

Aircraft in Hazard Area Results

Figures 5-1 and 5-2 show the range (over all the simulation iterations) of the number of aircraft inside an active Off-Nominal Failure AHA during each scenario for different traffic densities. This captures the number of aircraft from when an off-nominal event occurs, not just when ATC knows about it. These two figures are a graphic representation of the definitions of low, medium, and high traffic densities for each scenario.

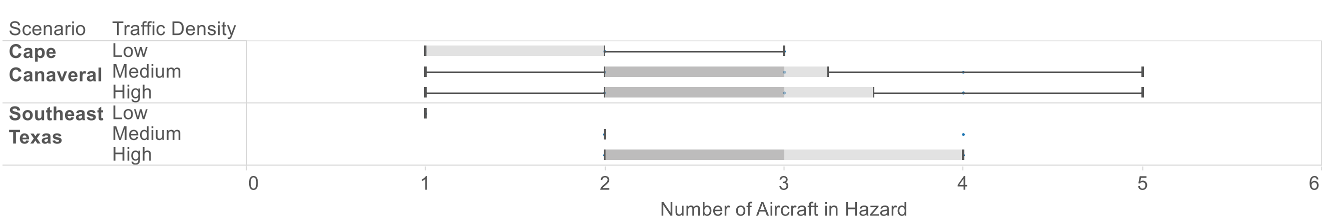

Figure 5-1. Range of Number of Aircraft in an Off-Nominal Failure AHA for scenarios 1 and 2.

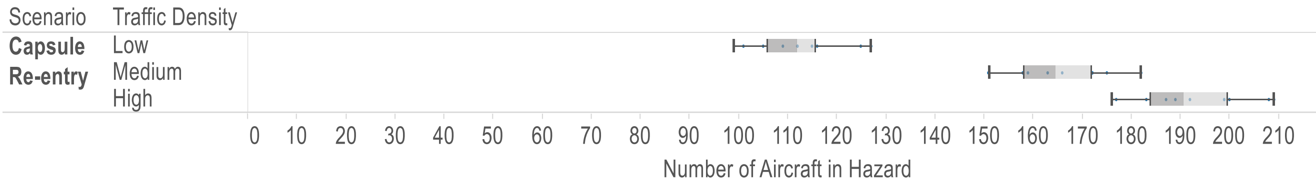

Figure 5-2. Range of Number of Aircraft in an Off-Nominal Failure AHA for scenario 3.

ATC Notification Delay Sensitivity Results

Figures 5-3 and 5-4 show the sensitivity of the time to clear and time in hazard to ATC notification delay (one minute, three minutes, and five minutes) for each scenario. They show that both metrics are sensitive to ATC notification delay.

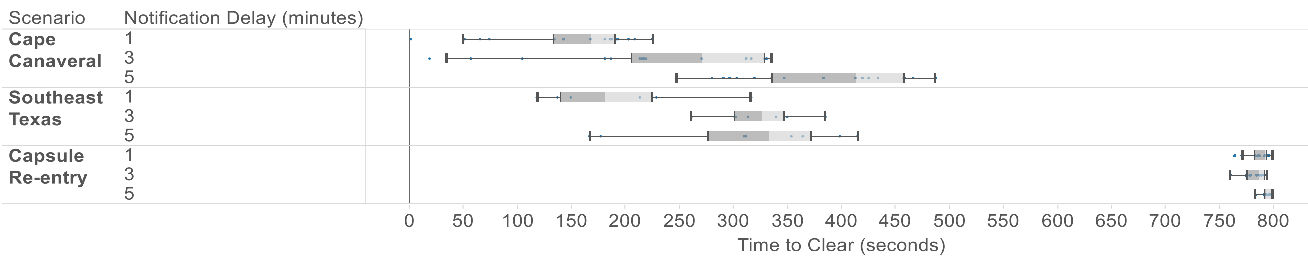

Figure 5-3. Sensitivity of Time to Clear to ATC notification delay.

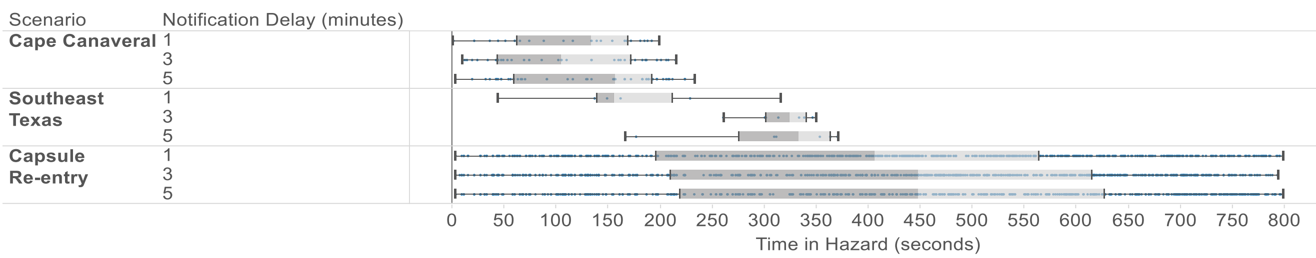

Figure 5-4. Sensitivity of Time in Hazard to ATC notification delay.

Traffic Density Sensitivity Results

Figures 5-5 and 5-6 show the sensitivity of the time to clear and time in hazard to traffic density (low, medium, and high) for each scenario. They show that both metrics are sensitive to traffic density.

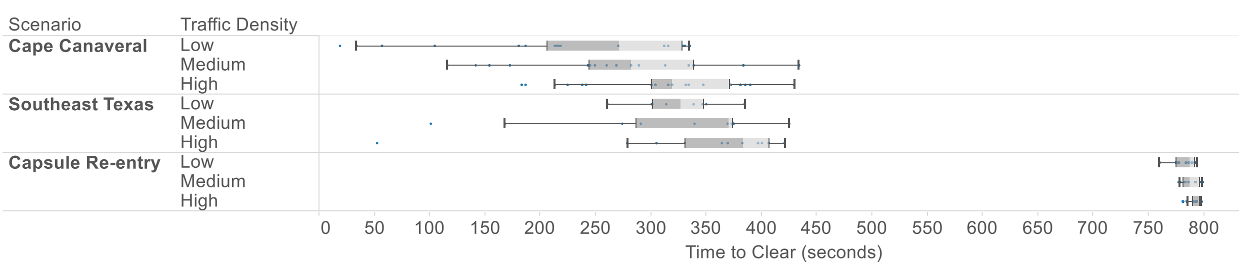

Figure 5-5. Sensitivity of Time to Clear to traffic density.

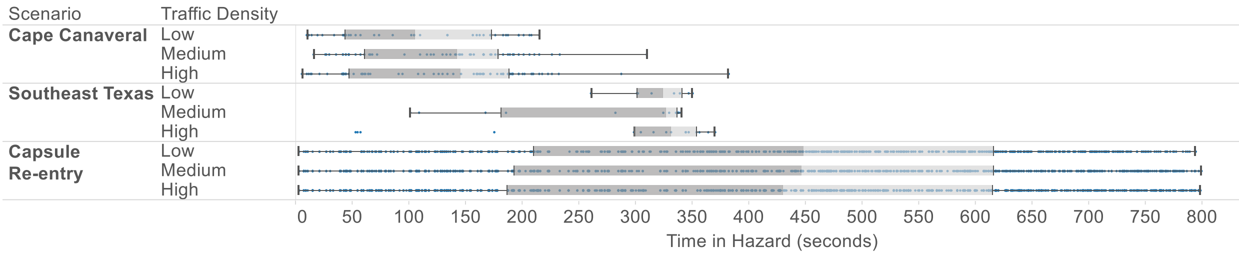

Figure 5-6. Sensitivity of Time in Hazard to traffic density.

Traffic Orientation Sensitivity Results

Figures 5-7 to 5-8 show the sensitivity of the metrics to the orientation of the traffic (in 30-degree bins). It can be seen that in all cases the flights with headings that align along the prevailing traffic patterns in each scenario have longer times in the hazard area and times to clear.

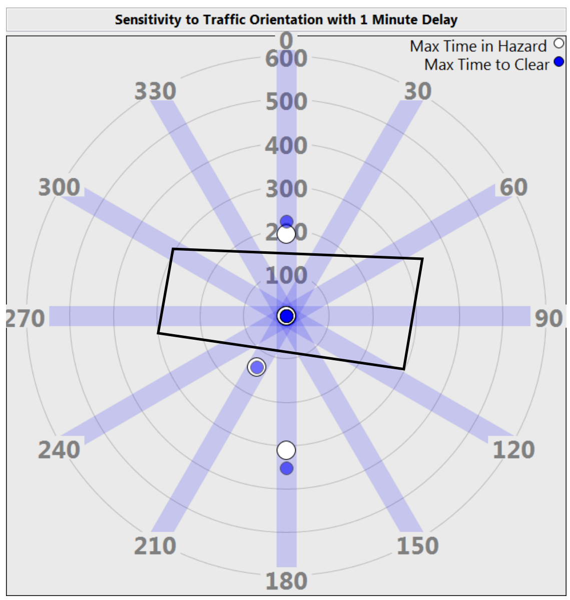

Figure 5-7. Scenario 1 sensitivity of Time in Hazard and Time to Clear to traffic orientation with AHA overlay.

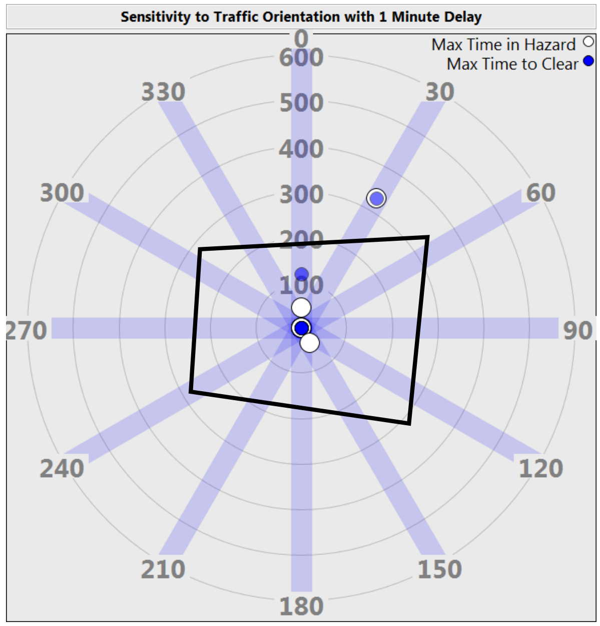

Figure 5-8. Scenario 2 sensitivity of Time in Hazard and Time to Clear to traffic orientation with AHA overlay.

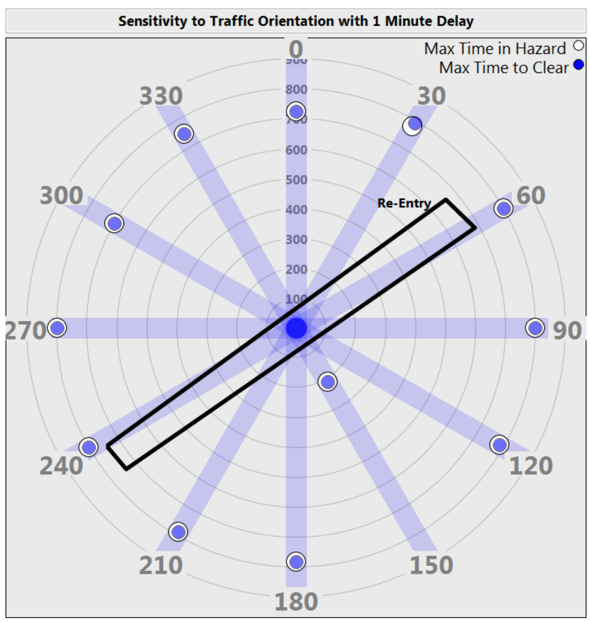

Figure 5-9. Scenario 3 sensitivity of Time in Hazard and Time to Clear to traffic orientation with AHA overlay.

Traffic Over Time

Figures 5-10 to 5-12 plots the average number of aircraft (from all scenario iterations) in an active AHA over time for each scenario with 1 minute ATC notification delays. This means that ATC starts executing commands to aircraft after 60 seconds in the plots. The traffic starts reducing accordingly. These charts give an idea of the rate of aircraft evacuation from an AHA, which appears to become linear in all of the scenarios shortly after activation. Further research could explore different evacuation strategies to see if it could change the rate of evacuation.

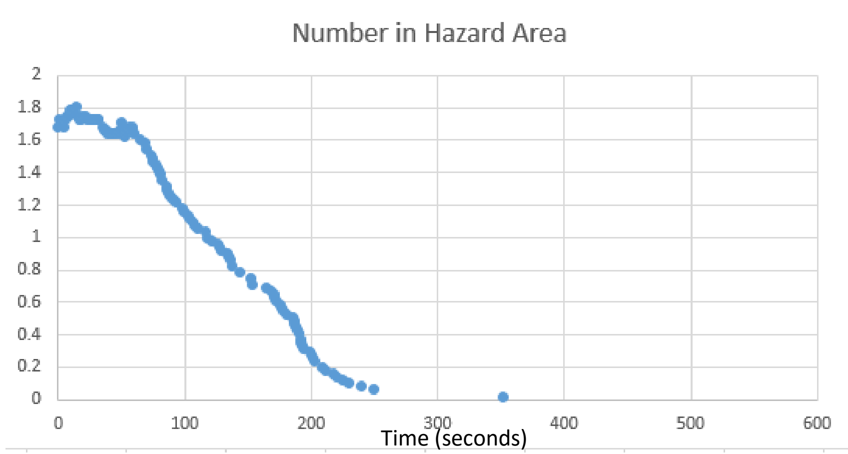

Figure 5-10. Scenario 1 average aircraft traffic in an active AHA over time with 1 minute ATC notification delay.

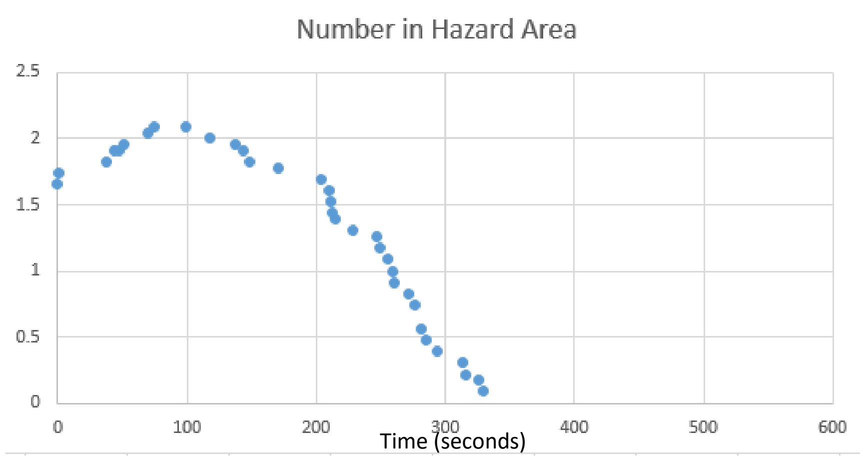

Figure 5-11. Scenario 2 average aircraft traffic in an active AHA over time with 1 minute ATC notification delay.

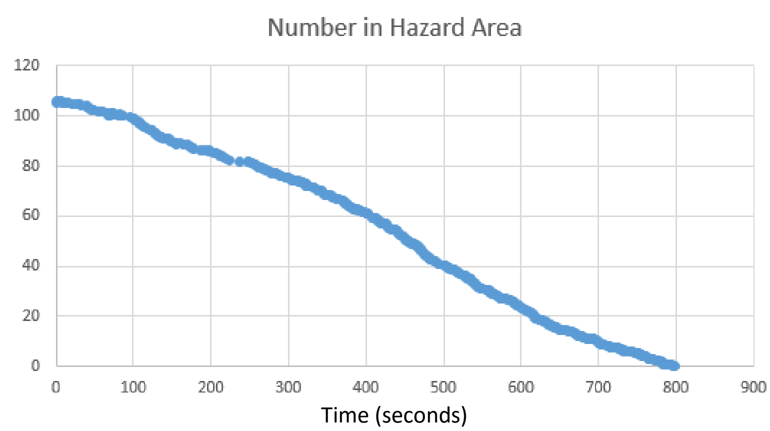

Figure 5-12. Scenario 3 average aircraft traffic in an active AHA over time with 1 minute ATC notification delay.

In summary, the simulation results indicate that the metrics are sensitive to the ATC delay, traffic orientation, and traffic density. Moreover, the time to clear is more sensitive to those factors than is the time in hazard. Time to clear is most sensitive to the ATC notification delay.

VI. Conclusion: A Capability to Help Enable Safe and Efficient Launch and Reentry Operations

MITRE is developing a modeling and simulation capability for evaluating LRV operations to examine the time for ATC to evacuate aircraft from dynamically activated AHAs. MITRE utilized the capability to examine three LRV scenarios based on past and potential future operations. Scenario 1 is a launch from KSC that would fail shortly after launch, which activates a dynamic AHA. Scenario 2 is a launch from southeast Texas that similarly fails shortly after launch and activates a dynamic AHA. Scenario 3 is an orbital reentry that fails during the de-orbit burn, which activates a dynamic AHA in the CONUS. MITRE examined how the sensitivity of metrics for an individual aircraft's time to exit the AHA and the time it takes to clear all aircraft out of the AHA to the factors of (1) traffic orientation, (2) traffic density, and (3) ATC notification delay. The results showed that the metrics were sensitive to the ATC notification delay, traffic density, and traffic orientation. The factors that affected the metrics the most were traffic orientation, traffic density, and ATC notification delay. The time to clear was more sensitive to those factors than the time in hazard metric.

This study further demonstrates MITRE's capability to answer important FAA questions such as what strategies and procedures ATC should utilize to maintain target levels of safety during these types of operations. The capability can be used to inform standards for surveillance and communications, and needed ATC automation to enable more efficient and safe LRV operations in the NAS. It can be used to assess the safety of a variety of LRV operations (including high altitude balloon operations) and trajectories. MITRE is working with the FAA to utilize this capability to examine potential strategies and methods that ATC could employ during off-nominal cases.

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