

FULL-ENVELOPE LAUNCH ABORT SYSTEM PERFORMANCE ANALYSIS METHODOLOGY

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The implementation of a new dispersion methodology is described, which disperses abort initiation altitude or time along with all other Launch Abort System (LAS) parameters during Monte Carlo simulations. In contrast, the standard methodology assumes that an abort initiation condition is held constant (e.g., aborts initiated at altitude for Mach 1, altitude for maximum dynamic pressure, etc.) while dispersing other LAS parameters. The standard method results in large gaps in performance information due to the discrete nature of initiation conditions, while the full-envelope dispersion method provides a significantly more comprehensive assessment of LAS abort performance for the full launch vehicle ascent flight envelope and identifies performance “pinch-points” that may occur at flight conditions outside of those contained in the discrete set. The new method has significantly increased the fidelity of LAS abort simulations and confidence in the results.

INTRODUCTION

NASA’s Orion Multi-Purpose Crew Vehicle (MPCV) is being designed to transport humans to destinations beyond low Earth orbit, including LaGrange Points, near-Earth asteroids, the Moon, and Mars¹. One of the primary design drivers for MPCV is to ensure crew safety. MPCV requirements specify that abort capability should be continuously available from the launch pad until the mission destination is reached². Aborts during the critical ascent flight phase require the design and operation of MPCV systems to escape from the Space Launch System (SLS) and return the crew safely to the Earth.

Ascent phase aborts are characterized by large changes in vehicle altitude, large attitude maneuvers, and large vehicle center-of-gravity movement and pose significant engineering challenges. Several ascent abort modes are being designed and analyzed to accommodate the velocity, altitude, atmospheric, and vehicle configuration changes that occur during ascent³. These modes provide abort coverage extending from the launch pad until the MPCV achieves a sustainable orbit. Analyzing these modes involves an evaluation of the feasibility and survivability of each abort mode and an assessment of the abort mode coverage using the current baseline vehicle design. Factors such as abort system performance, concept of operations, crew load limits, thermal environments, crew recovery, and vehicle element disposal are investigated to determine if the current vehicle requirements are appropriate and achievable^{4,5,6}.

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Aborts occurring between launch and the Launch Abort System (LAS) jettison event during SLS second-stage flight are performed using the LAS. During this type of abort, the LAS abort motor is used to pull the Crew Module safely away from the SLS and Service Module. LAS aborts are characterized by high aerodynamic loads induced by low altitude maneuvers and high accelerations caused by the launch abort motor.

Previously, LAS analyses were performed only at specific points along the launch vehicle ascent trajectory. LAS performance studies began to indicate that aborts initiated at those points may not encompass the worst overall performance for the LAS. For example, early in the LAS design, the Mach 1 abort condition was assumed to produce worst-case performance. Several simulation studies of LAS aborts in this region indicated that performance may be worse at a condition other than Mach 1. In order to identify the true “pinch point” for performance (i.e., abort conditions causing largest numbers of unsuccessful aborts), a new performance assessment methodology was developed where the abort time was uniformly dispersed in Monte Carlo simulations from the ground to nominal LAS jettison (or another predetermined maximum altitude) along the launch vehicle ascent.

OVERVIEW OF ORION MULTI-PURPOSE CREW VEHICLE

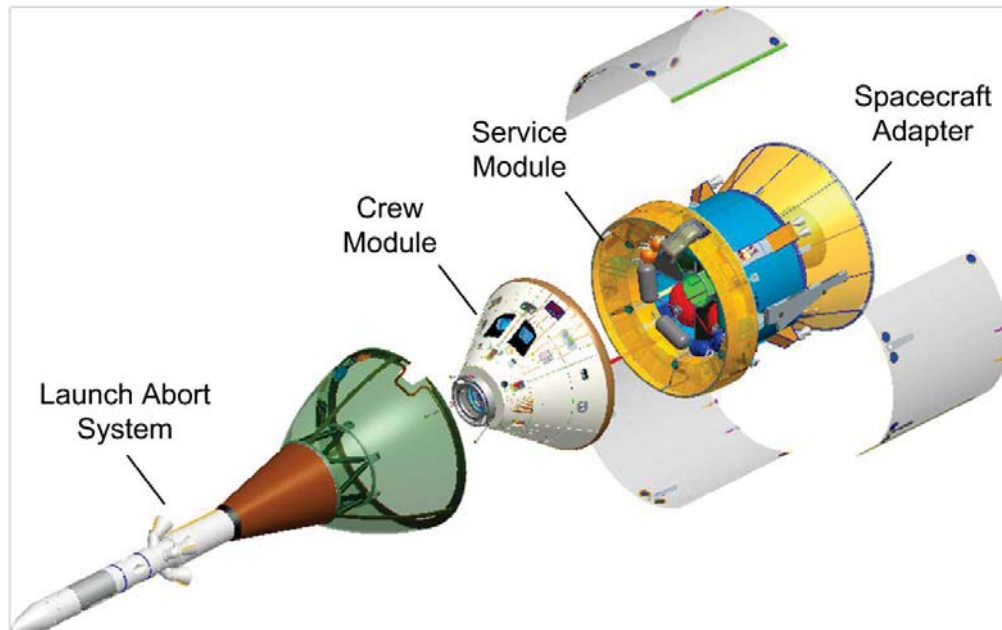


Figure 1. Orion Multi-Purpose Crew Vehicle (MPCV).

The Orion MPCV is composed of four main elements: the LAS, the Crew Module, the Service Module, and the Spacecraft Adapter, as shown in Figure 1. The LAS is designed to provide a reliable abort capability for aborts that occur within the atmosphere. The Crew Module provides a safe, habitable volume for the crew during launch, spaceflight, and return from the mission destination. The Service Module provides additional resources necessary to support the primary mission, including power and maneuvering capability. The Service Module is also used to provide abort capability for exo-atmospheric aborts. The Spacecraft Adapter provides the interface between the spacecraft and the SLS. The term Launch Abort Vehicle (LAV) will be used to refer to the LAS and Crew Module together, prior to jettison of the LAS.

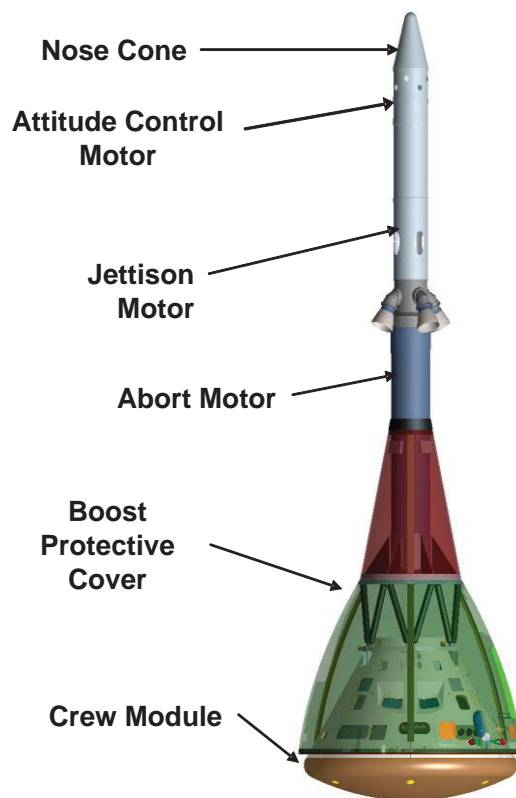


Figure 2. Launch Abort Vehicle (LAV).

As shown in Figure 2, the LAV consists of an Abort Motor to provide the SLS/LAV abort separation function, an Attitude Control Motor to provide attitude and rate control, and a Jettison Motor for Crew Module/LAS separation. The Attitude Control Motor consists of a throttleable solid rocket system. The LAS also provides a Boost Protective Cover that shields the Crew Module from debris and the aero-thermal environment during ascent.

ABORT PERFORMANCE ANALYSIS METHODOLOGY

LAS abort performance analysis involves an evaluation of the feasibility and survivability of a LAS abort using the current baseline vehicle design. These studies and design trades are being conducted so that more informed decisions can be made regarding the vehicle requirements, design, and operations.

The analysis presented in this paper was performed using the ANTARES simulation⁷. ANTARES is a code that uses the Trick simulation environment for defining and tying together various dynamical and environment models, written in either C or FORTRAN, for 6-DOF simulation execution.

Previously, the simulation activity was divided into two parts⁸. The first part took the form of an abort trajectory survey, where a series of aborts were simulated from regularly-spaced altitude intervals from the pad to the nominal LAS jettison altitude. No dispersions were applied in this survey. All model and system parameters were maintained at their nominal values. The controller performance was then evaluated based on performance metrics determined by the vehicle re-

quirements. For the second part, the simulation analysis consisted of 2,000 Monte Carlo dispersions at specific conditions along the ascent, detailed in Table 1. These conditions were selected based on their perceived importance to varying abort conditions along the ascent. The abort initiation condition was held constant while dispersing other LAS parameters, including abort motor misalignment and thrust level output, aerodynamic data, mass properties, and atmospheric properties. Performance metrics were then assessed for each of those abort scenarios. The success/failure rate of each regime was weighted by a time-weighting factor to produce an overall success/failure rate that represented the entire portion of the SLS ascent where the LAS is responsible for aborts. This time-weighted averaging technique is described in further detail in the section titled, “Overall Success Calculations.”

Table 1. Abort conditions.

Type of Abort	Abort Condition
Pad	pad abort
Low	2.4 km (8,000 feet)
Mach 1	Mach 1
Max Q	maximum dynamic pressure
Mid	21.3 km (70,000 feet)
High	36.6 km (120,000 feet)

The prior standard method resulted in large gaps in performance information due to the discrete nature of abort initiation conditions. Pinch points may occur at flight conditions outside of those contained in the discrete set. Until the development of the full-envelope dispersion method, it was assumed that the Mach 1 condition produced the worst performance for some of the LAV performance metrics. The initial use of the full-envelope dispersion method revealed that the true “pinch-point” was actually at a condition between Mach 1 and maximum dynamic pressure.

The full-envelope dispersion method was developed to address those information gaps. The new analysis method disperses the abort initiation conditions along with the abort vehicle parameters. The performance results from the dispersed trajectories are binned in a histogram-type plot to show performance versus abort initiation condition, such as altitude or time. The example provided in this paper used a uniformly dispersed abort time from the pad to nominal LAS jettison. The total number of runs for the Monte Carlo was 199,989. This number was chosen simply as a large number of runs to provide information concerning convergence of metric failure rates and is a much larger number than is used in current LAS performance analyses. The uniformly distributed abort time resulted in 823 dispersed runs for each second from launch to nominal LAS jettison time, a period of 243 seconds.

The performance metrics that are prescribed for the abort are intended to ensure that controlled flight is maintained, that structural constraints are observed with respect to aerodynamic loading, and that the Crew Module is left in a flight dynamic condition that is appropriate for successful drogue deployment following the LAS jettison event. These performance metrics take the form of limits that are applied to allowable variations in angle of attack, sideslip, body rates, dynamic pressure, and Mach number values at certain points along the simulated abort trajectory⁸. One of the key performance metrics is that the LAV maintain nose-forward flight prior to start of the reorientation maneuver. This metric is often called the tumbling metric and will be used as an

example throughout this paper. Figure 3 shows the percent tumbling runs from a full-envelope Monte Carlo run set. The failure percentage for tumbling is shown in each 2-second time bin along the launch vehicle ascent. Each bin shows the percentage of runs failing the tumbling metric out of all the runs in that bin. The yellow dashed lines indicate abort initiation conditions at which the Mach 1 and maximum dynamic pressure (MaxQ) standard dispersions were previously run. These lines are representative of the average time at which the Mach 1 and maximum dynamic pressure conditions occur over each of the dispersed launch vehicle trajectories. The most important result to draw from this figure is that the regions near Mach 1 and maximum dynamic pressure, where aborts were previously run, is not the abort condition for the highest percentage of tumbling runs. Since the early LAS design stage where LAS tumbling was a much larger issue, design changes have resulted in much lower tumbling rates. However, as seen in Figure 3, tumbling still occurs in this regime under certain vehicle parameter dispersions. Therefore, the time-weighted averaging technique may not be providing the most accurate pass/fail rate over the entire LAS abort coverage range. This figure also provides a graphic illustration of the LAS abort “black-out zone,” or the region where abort performance is severely degraded. By using this method, the LAS can now be optimized to reduce failure rates at the worst abort conditions and reduce the “black-out zone.” All of the performance metrics can be presented in this manner, although not shown here.

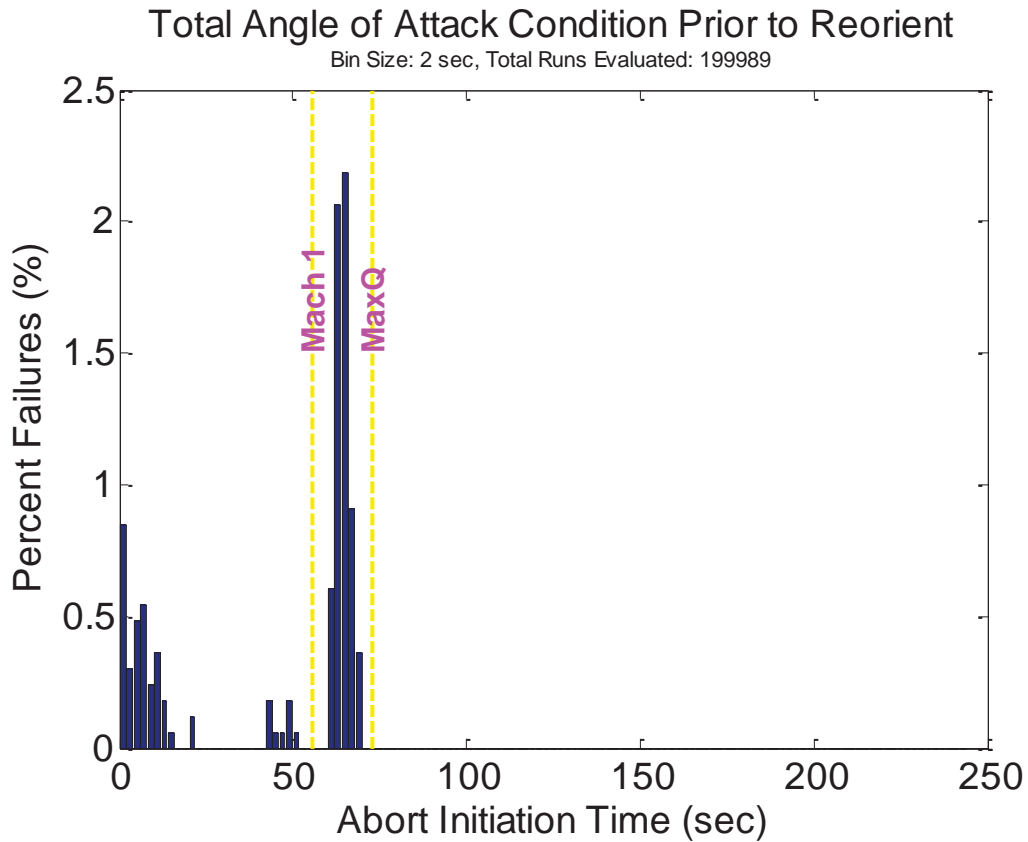


Figure 3. Percent Tumbling versus Abort Initiation Time.

The bin size of 2 seconds was selected based on a range that provided the most useful information. Choosing larger bin sizes produces results that are not as informative in terms of performance with respect to abort initiation condition, and choosing smaller bin sizes results in a distribution that is too noisy with no clear visible trends. A brief study was conducted to determine the appropriate histogram bin size. Initial testing suggested a bin size that was near the 2-second bin size already selected.

Practical Number of Runs

Convergence of failure percentages were assessed to identify the minimum number of runs necessary to ensure reliable results, while also providing the lowest processing time possible. Several methods were employed to determine the appropriate number of runs. These methods were chosen as a practical means for selecting a number of runs that is feasible for the numerous design trade studies and configuration changes that are completed as the design of the LAV progresses. It is possible that for the final vehicle configuration, more runs will be necessary to more accurately characterize the Loss-of-Crew statistical analysis for the combined launch vehicle and LAV.

The first and simplest method employed was a “sanity check” on the known failure rates of metrics. For example, low altitude aborts produce some level of water depth line violations. If too few runs are initiated along the ascent, no water line violations are presented in the post-processing analysis. This result is not consistent with known violation rates based on previous analysis. A greater number of runs along the ascent will produce those known violations.

Figure 4 shows the tumbling percentage versus abort initiation time for Monte Carlos where 10,000 runs were initiated from the pad to nominal LAS jettison, and Figure 5 shows the tumbling percentage for a Monte Carlo set with 100,000 runs. Clearly, the percent failures in each bin are different. The 10,000-run Monte Carlo set does not match the expected percent tumbling as seen in the 199,989-run set in Figure 3. The 100,000-run set produces results that are more similar to the results seen in the 199,989-run set.

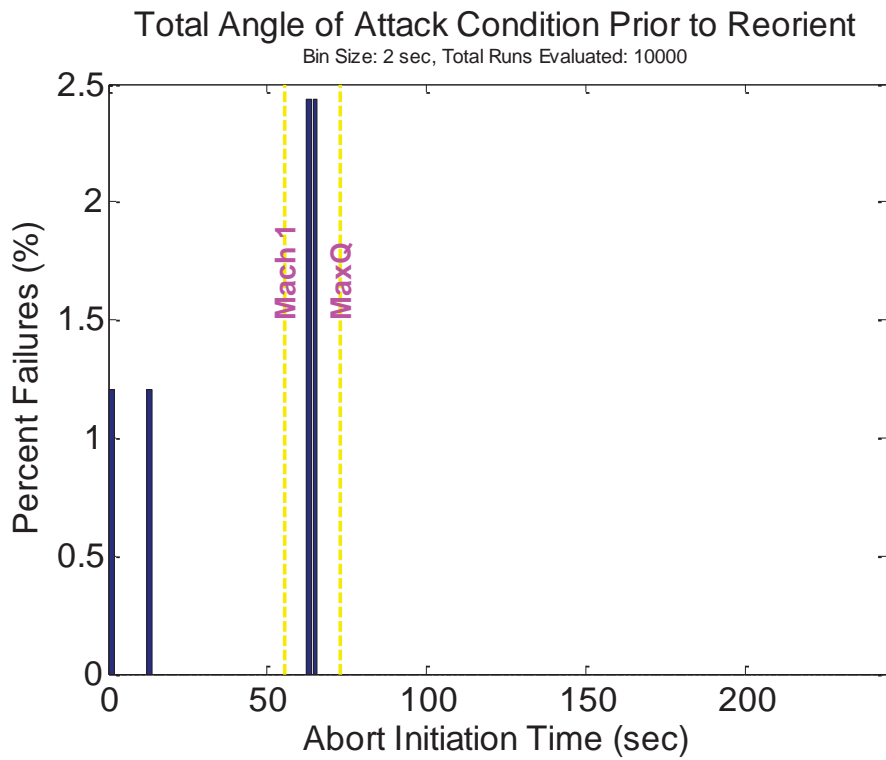


Figure 4. Tumbling versus Abort Initiation Time for 10,000-Run Monte Carlo.

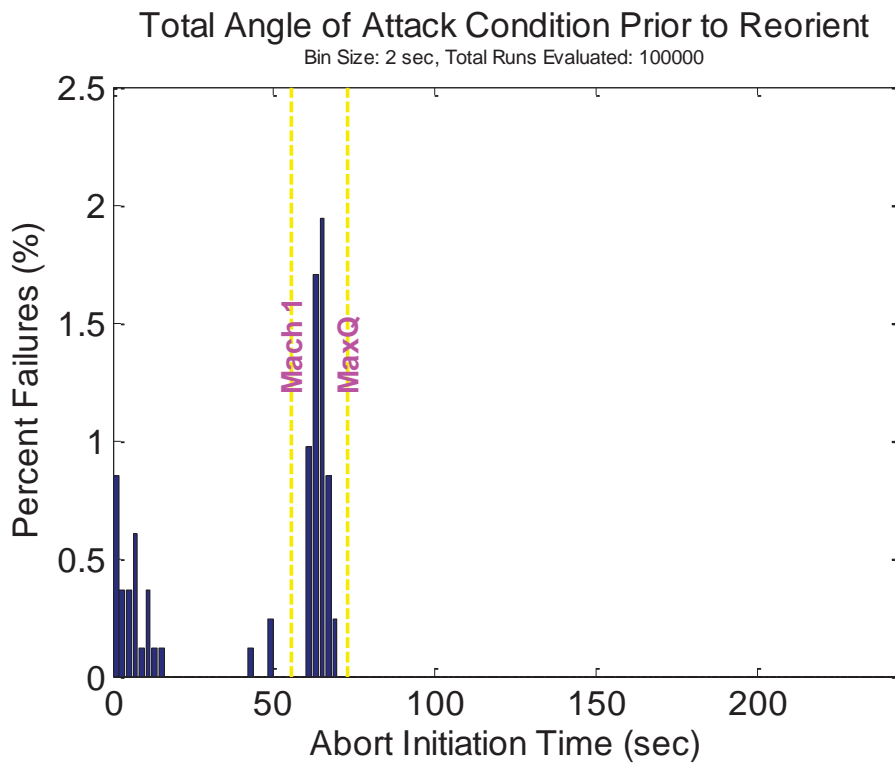


Figure 5. Tumbling versus Abort Initiation Time for 100,000-Run Monte Carlo.

Another way to verify that the failure percentage has converged is to examine the percent violations for a full-envelope performance assessment as the number of runs increases. When these percentages level out and become stable, enough cases have been run, and convergence has been achieved. Figure 6 shows the percent tumbling cases from only the bin with the maximum tumbling rate (64-66 seconds) as the number of runs within that bin increases. Figure 7 shows the total percent tumbling cases for the entire full-envelope Monte Carlo. As the number of runs increases, the percent of failures settles. Further analysis, not shown in this paper, included examination of convergence in each altitude bin, as well as convergence of the other metrics used to evaluate abort performance. This type of analysis indicated that about 50,000 runs may be enough to ensure accurate performance metric results in the abort region from the ground to nominal LAS jettison.

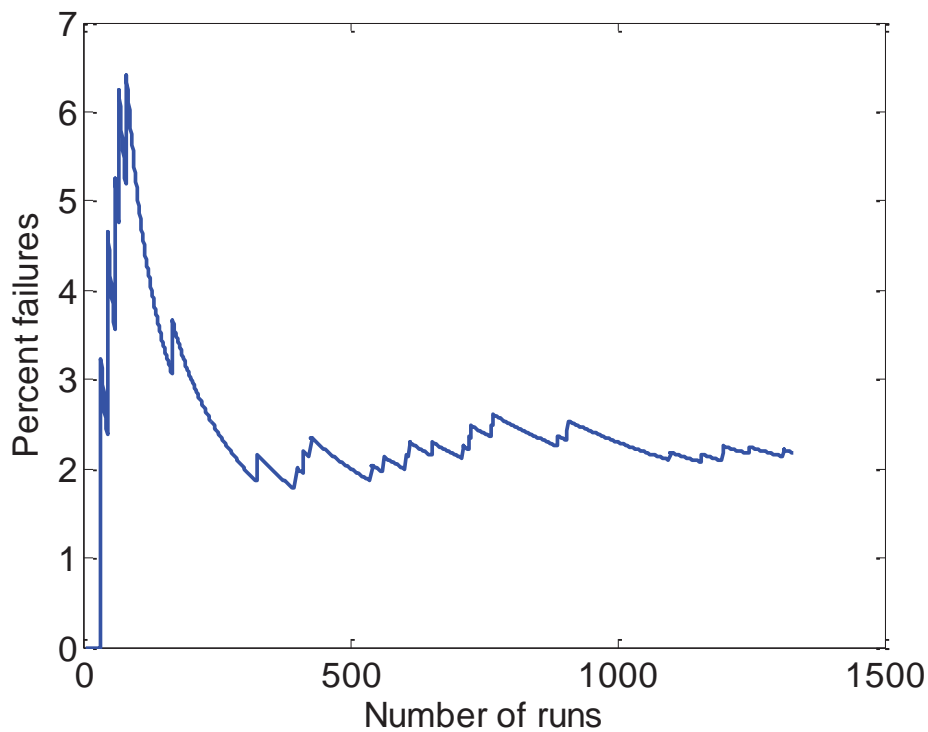


Figure 6. Convergence of Tumbling Rate in Bin with Maximum Tumbling Rate.

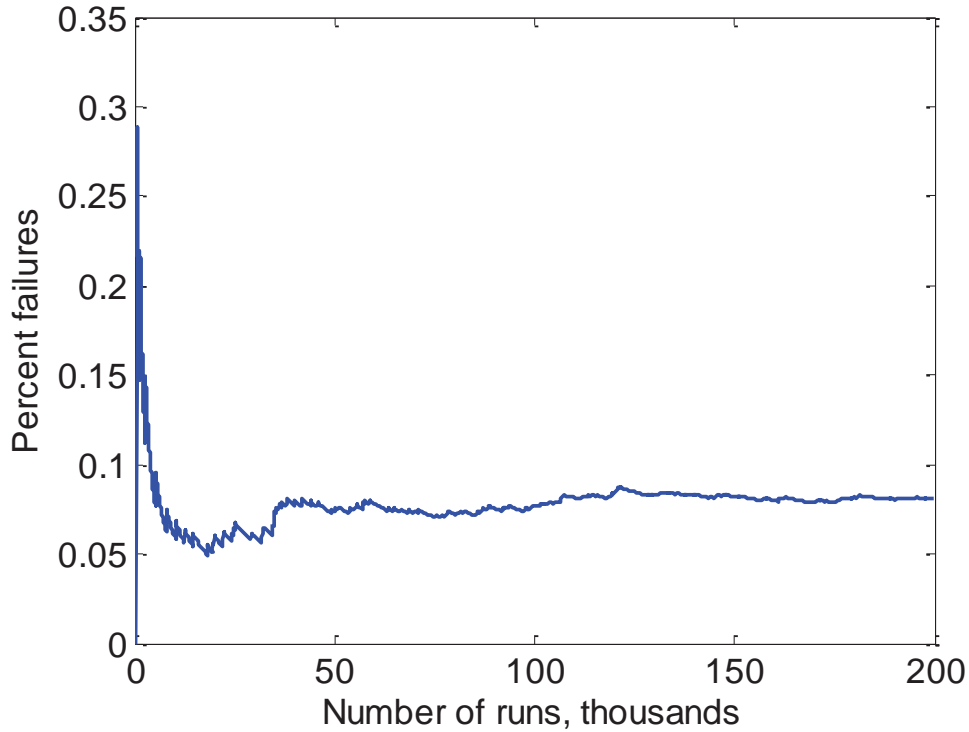


Figure 7. Convergence of Tumbling Rate for Entire Full-Envelope Scenario.

In addition to the simplistic methods described above, another approach was taken to determine a sufficient number of Monte Carlo runs to compute the Loss-of-Crew (LOC) failure probabilities. Reference [9] provides guidance on the number of runs necessary to compute failure probabilities with a desired level of confidence. Using the tumbling violations from the 199,989-run Monte Carlo set previously described, and assuming a 90% desired confidence level on the computed probabilities, the minimum number of runs required can be calculated for each 2-second bin. Using the recommended acceptable errors described in the paper, the total number of runs required is nearly 250,000. However, this is mostly due to the large number of runs necessary in the low-failure rate bins. Allowing for a higher acceptable error in these bins (such that the tumbling rate could be no more than 5%, for example) results in a lower number of runs required in those regions. Figure 8 shows the estimated percent tumbling for each 2-second bin along with the number of runs required to demonstrate a 90% confidence in the results.

The minimum number of runs necessary for reliable simulation performance results will be re-evaluated as the LAS design evolves. The current method employed by the Abort Performance Working Group forces varying numbers of runs along the launch vehicle ascent. For example, from the pad to 100 seconds, 300 runs per second are drawn as initial conditions, and from 100 seconds to nominal LAS jettison, 60 runs per second are drawn as initial conditions. This type of method was employed to satisfy the required confidence and allowable error based on certain performance metrics that are of interest in the LAS design at this time. The number of runs used for these types of large flight envelope simulations should be carefully chosen based on the use of the simulation data and re-evaluated on a regular basis.

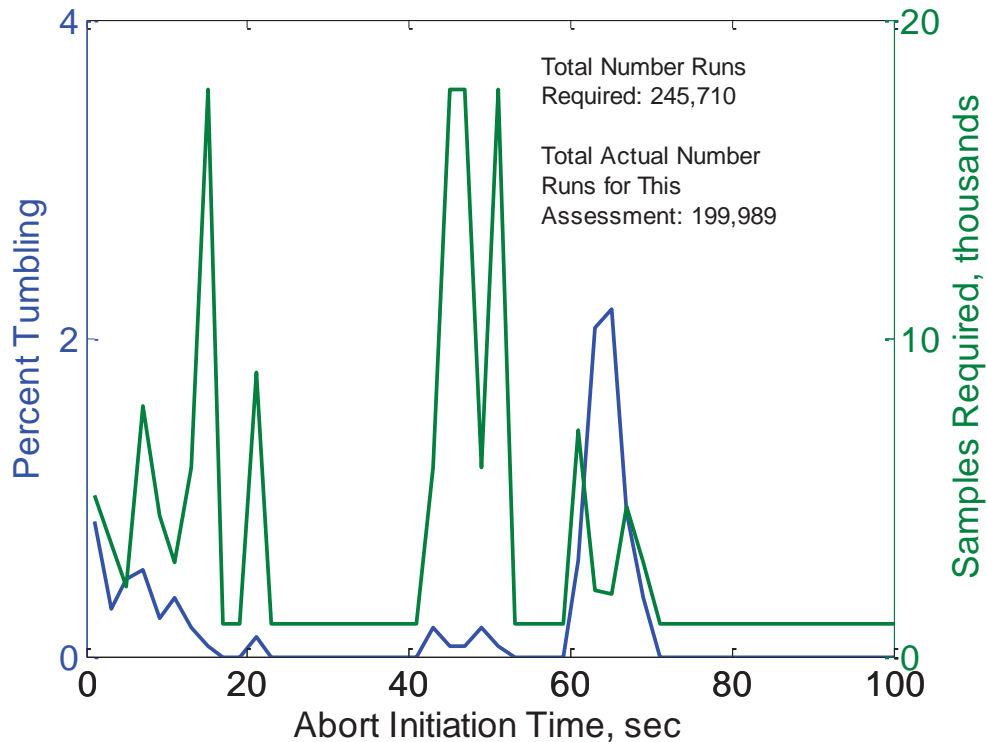


Figure 8. Estimated Percent Tumbling and Number of Runs Required.

Overall Success Calculations

The time-weighted averaging technique is described by an MPCV requirement. The requirement is designed to weight LAS Monte Carlos at specific conditions along the launch vehicle ascent. To calculate success/failure rate over the entire ascent, each Monte Carlo at the specific LAS abort regime produces a failure rate that is weighted by the time weighting factor. The results are then summed to produce one failure rate for LAS aborts. Table 2 shows the weighting factors for each LAS abort regime.

Table 2. Time-weighted averaging technique.

LAS Abort Regime		Time Weighting Factor
Near Pad	0 – 0.3 km	0.06
Low Altitude	0.3 – 4.6 km	0.16
Mach 1	4.6 – 7.6 km	0.07
Max Q	7.6 – 16.8 km	0.14
Mid Altitude	16.8 – 27.4 km	0.12
High Altitude	27.4 – 85.3 km	0.45

Table 3 shows the overall success rate for the time-weighted averaging technique based on individual 2,000-run Monte Carlos run at the specific abort conditions described in Table 1. The full-envelope method results in an overall tumbling metric satisfaction rate of 99.92%, while the time-weighted averaging technique results in a success rate of 99.84%. The time-weighted averaging technique has deficiencies in that it assumes levels of performance are more consistent along the launch vehicle ascent than is really the case. Figure 9 illustrates this concept by showing the tumbling metric failure rate versus abort initiation altitude for the full-envelope technique versus the time-weighted averaging technique. Not only is the full-envelope dispersion method more informative in terms of performance along the launch vehicle ascent, it produces a more reliable success rate prediction for this type of large-flight-envelope vehicle.

Table 3. Tumbling Metric Success Rate Based on Time-Weighted Averaging Technique.

Time Weighting Factor	LAS Abort Regime	No SLS Failures
0.06	Near Pad	99.25%
0.16	Low Altitude	99.85%
0.07	Mach 1	100%
0.14	Max Dynamic Pressure (Max Q)	99.35%
0.12	Mid Altitude	100%
0.45	High Altitude	100%
	Time Weighted Average	99.84%

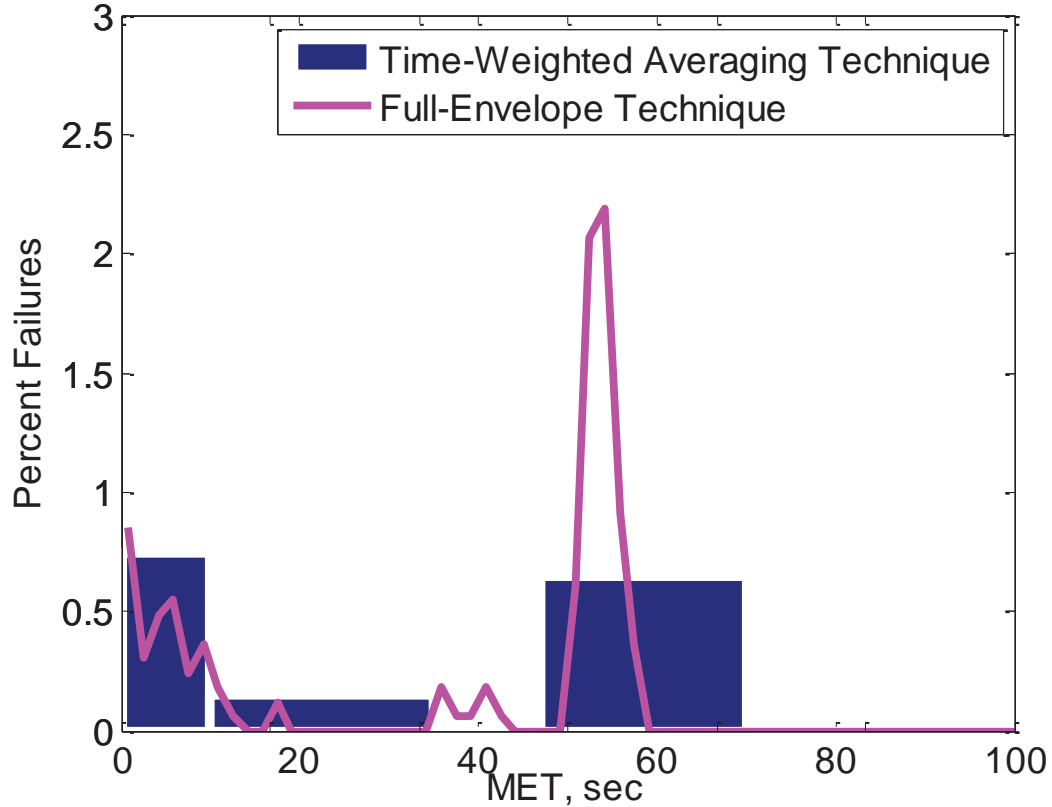


Figure 9. Comparison of Tumbling Metric Failure Rate for Time-Weighted Averaging and Full-Envelope Techniques.

During the development of this analysis method, the issue of whether to generate abort initial conditions based on a uniform time or uniform altitude was addressed. The method of using the time-weighted averaging technique is meant to roll up the success rate across the entire ascent based on time spent in each ascent regime. Since altitude and time along the ascent do not have a linear relationship, using a uniform time distribution and altitude distribution will produce different results. A uniform altitude distribution will produce many more runs at the beginning of ascent when the vehicle velocity is relatively low. This will weight the overall performance results towards the lower altitude performance rates. Using a uniform time distribution will equally weight the performance with time with the same philosophy as the time-weighted averaging requirement.

Using a uniform time distribution to produce the initial conditions does not limit the presentation of performance as a function of time. The performance can be shown as a function of altitude, Mach number, or time, for example. Showing the metrics in terms of various conditions along the ascent can be informative for concept-of-operations and controller design of the abort system.

Example of Use of Full-Envelope Analysis Method

An example of the full-envelope dispersion method is the abort motor offset angle study described in Reference [10]. To assess the impact of the abort motor thrust alignment on LAV tumbling, the offset angle of the thrust vector was varied. Figure 10 shows the percent tumbling for the portion of the SLS ascent until nominal LAS jettison. The full-envelope performance analysis method allows a comprehensive assessment of performance at flight conditions. In this example, the method allows the project to make a decision on a vehicle parameter based on both the peak tumbling rate and the length of the potential “black-out zone” (length of time the performance is degraded). This method also ensures that any potential vehicle change will not negatively impact another abort condition, or ascent region.

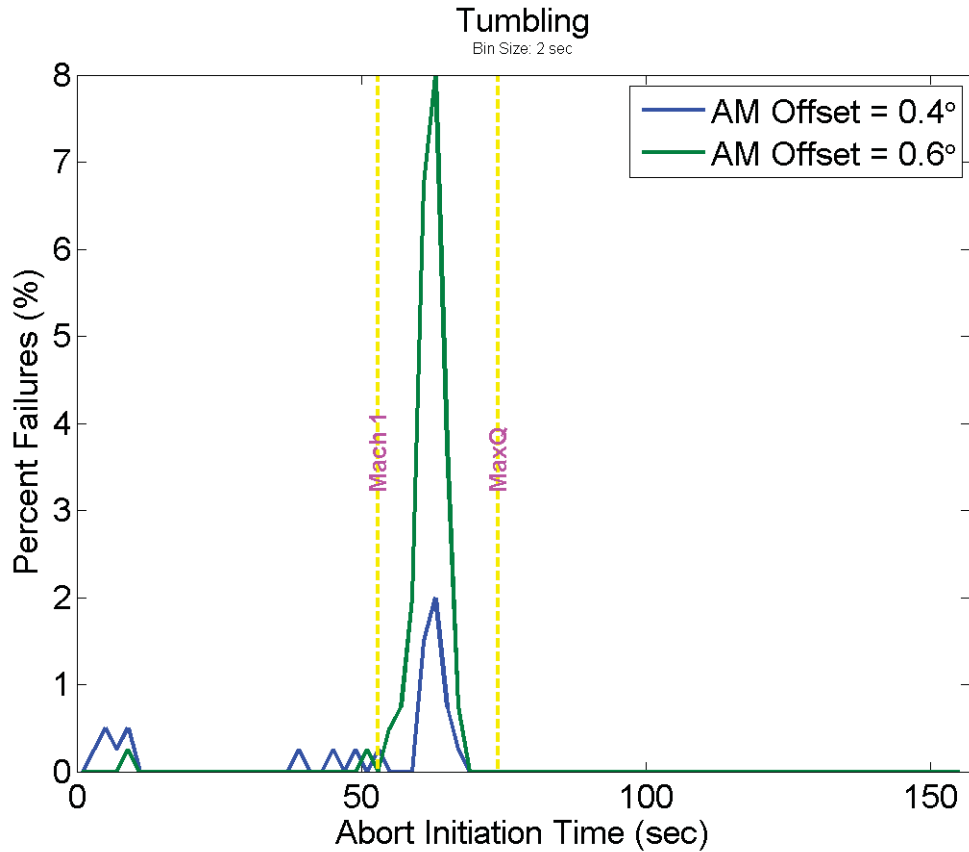


Figure 10. LAV Tumbling Failure Rate versus Abort Initiation Time Along the SLS Ascent Trajectory for Abort Motor Offset Angles of 0.4 and 0.6 degrees.

CONCLUSIONS

The development of the full-envelope LAS performance analysis dispersion methodology has been described. The full-envelope dispersion method disperses abort initiation time along with all other LAS parameters during Monte Carlo simulations. This method contrasts the standard methodology which assumes that an abort initiation condition is held constant (e.g., abort initiated at altitude for Mach 1, altitude for maximum dynamic pressure, etc.) while dispersing other LAS

parameters. Performance “pinch points” that occur at flight conditions outside of those contained in the discrete set are identified with the new method, thus providing a significantly more comprehensive assessment of LAS abort performance for the full launch vehicle ascent flight envelope. The number of runs is optimized on a regular basis using the methods described in this paper to ensure convergence and minimize processing time.

Time-weighted averages computed from the standard Monte Carlos at specific altitude/conditions were compared to results of the full-envelope dispersion method. The time-weighted averaging technique has deficiencies in that it assumes levels of performance are more consistent along the launch vehicle ascent than is really the case. The full-envelope dispersion method produces a more reliable success rate prediction for this type of vehicle.

The new method has significantly increased the fidelity of LAS abort simulations and confidence in the results. The method has been shown as providing a more comprehensive and more accurate assessment of performance, better information to other design teams, and that data could be generated in a timely manner.

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