Synthesizing a New Launch Vehicle Failure Probability Based on Historical Flight Data

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Abstract: New launch vehicles have historically had significantly higher failure rates in early flights than what has been predicted using Probabilistic Risk Assessment - PRA. This is because PRAs typically model a mature vehicle where a significant portion of the early failure probability contributors have been eliminated due to testing and improvements after actual field operation. To capture a more accurate early flight failure probability estimate, this paper develops a method that estimates ascent failure probability starting with the first flight based on historical launch vehicle records. With new launch vehicles being developed, such as the Space Launch System - SLS, a PRA model must be extended to cover early flight failure probability contributions that are either not covered in the mature-vehicle PRA or are underestimated. These failure probability contributions include design errors, quality control deficiencies, installation errors, and environmental impacts. There are also failure dependencies due to systemic errors that still exist due to limited entire-system testing.

Keywords: PRA, Launch Vehicles, Early Failures.

1. INTRODUCTION

New launch vehicles have historically had significantly higher failure probabilities in early flights than what has been predicted using Probabilistic Risk Assessment - PRA. This is because PRAs typically model a mature vehicle where a portion of the failure probability has been mitigated due to testing and improvements after actual field operation. To capture a more accurate early flight failure probability estimate, this paper develops a method that estimates ascent failure probability starting with the first flight based on historical launch vehicle records. With new launch vehicles being developed, such as the Space Launch System - SLS, a PRA model must be extended to cover early flight failure probability areas that are either not covered in the mature-vehicle PRA or are underestimated. These failure probability areas include design errors, quality control deficiencies, installation errors, and environmental impacts. There are also failure dependencies due to systemic errors that still exist due to limited entire-system testing.

The Launch Vehicle and Spacecraft Early Failure (LVSEF) database, otherwise known as the early failure database, has been developed to be used in qualitative and quantitative assessments of launch vehicles and spacecraft. The early failure database documents launch vehicle and spacecraft flight histories including successes and failures, failure descriptions and failure causes. This paper builds on the launch failure probability work done originally for Ares I-X [1], and provides an example of the use of the database to assess the first launch failure probability of a hypothetical new launch vehicle that is similar to those being designed.

2. LVSEF DATABASE DESCRIPTION

The early failure database is an Excel based tool that includes both launch vehicle flight history and design information. Specifically, it includes:

- US and worldwide launches from 1980 through December 2017,
- Design information for each launch vehicle model,
- The outcome of each launch, success/failure (failure can be loss of mission or vehicle),
- Descriptions of failures,
- Categorizations of where failure occurred and the effect, and

- Categorizations of causes.

The early failure database may be used to obtain baseline quantitative assessments for new launch vehicles. The baseline quantitative estimate of the failure probability that is obtained may then be updated with knowledge of the specific assurance program that is applicable or is planned. This section describes how the baseline estimate can be obtained and how it can be updated and be refined based on assessment of a specific assurance program including an assessment of the measures taken for potential relevant historical failures previously identified. The probability of failure assessed in this section is based on Loss of Mission (LOM) which would include a Loss of Vehicle (LOV).

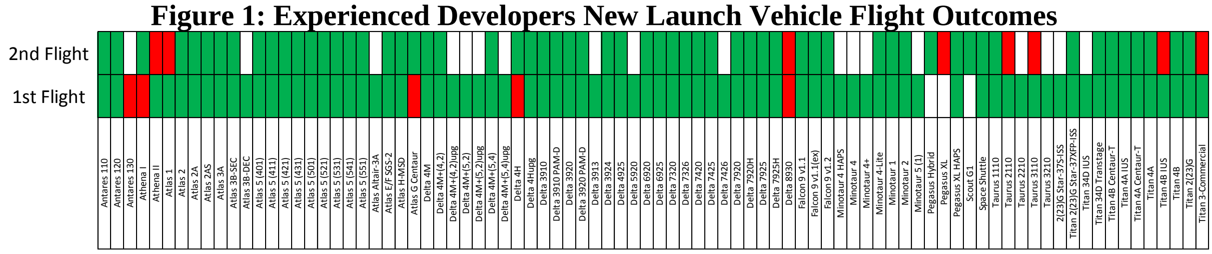
3. QUANTITATIVE ASSESSMENTS FOR NEW LAUNCH VEHICLES

3.1. Empirical Baseline Assessment

To estimate a baseline failure probability the relevant flight history of new launch vehicles is used. For this assessment, a "new launch vehicle" is defined by a either a completely new vehicle design, or a new vehicle model that includes a significant modification to an existing model, e.g. a new engine, different upper stage, different configuration of strap-ons, etc. The database was used to identify the outcomes of the first two launches of new launch vehicles. Only "experienced" launch vehicle developers (must have at least 5 successful launches of one or more vehicles) were considered for the quantitative assessments. Figure 1 shows histories for the individual launch vehicles and the outcomes for the first two flights. The first two flights were used because the failure histories appear to be similar and the sample size is increased. A green bar indicates a success and a red bar indicates failure. A blank implies that there was no second flight, or in some of cases the developer was considered a new developer for the 1st flight or the first flight was prior to the 1980 cutoff for the database.

From the data in Figure 1, there were 151 total launch attempts with 15 failures. Assuming a binomial distribution, the data yields an average failure probability estimate of 1 in 10 and 5th and 95th confidence bounds of 1 in 16 and 1 in 7 respectively. The confidence bounds are the bounds on the average value and do not incorporate differences in the individual assurance program or the specific assurance program for a new launch vehicle.

Figure 1: Experienced Developers New Launch Vehicle Flight Outcomes



3.2. More Specific Baseline Estimate of the Failure Probability by Synthesizing Individual System Failure Probabilities

Launch vehicles can vary in their complexity with differing number of engines, stages, etc., and one with more complexity may be assumed to have a higher probability of failure than a simpler launch vehicle. Using the early failure database, a more specific estimate for a new launch vehicle can be made using the launch statistics of individual design elements.

3.3. Developing Design Element Failure Probabilities

Consider a new launch vehicle with the high level design shown in Table 1. In addition to the design elements in the table, each launch vehicle is assumed to have avionics and thrust vector control (TVC) for each liquid engine and solid rocket motor.

Table 1: General Design Elements of Hypothetical New Launch Vehicle

Basic Design Elements	
Number of Stages	2
Fairing Separations	1
1st Stage Design Elements	
Number of Liquid Engines	3
Number of Solid Motors	2
Upper Stage Design Elements	
Number of Liquid Engines	2

Using the failure categorizations provided in the early failure database along with the design information also contained in the database, Table 2 shows the failure probability from the 1st and 2nd flight for US launch vehicles by design element that are applicable to the hypothetical launch vehicle.

Table 2: Failures by Design Element on the First 2 Flights

Design Element	Failures	Number of Design Elements Flown	Failure Probability
Avionics	2	151	1.32E-2
1st Stage Liquid Engines	2	203	9.85E-3
Solid Propulsion	1	161	6.21E-3
Upper Stage Liquid Engines	3	148	2.03E-2
Stage Separation	3	220	1.36E-2
Fairing Separation	3	149	2.01E-2
Thrust Vector Control	1	512	1.95E-3

Because most of the probabilities of failure in Table 2 are on a per design element basis and the new launch vehicle has multiple engines, solid rocket motor, etc., the overall probability of failure of each design element must take into account the number of elements as shown in Table 3.

Table 3: Estimated Design Element Failure Probabilities for New Launch Vehicle

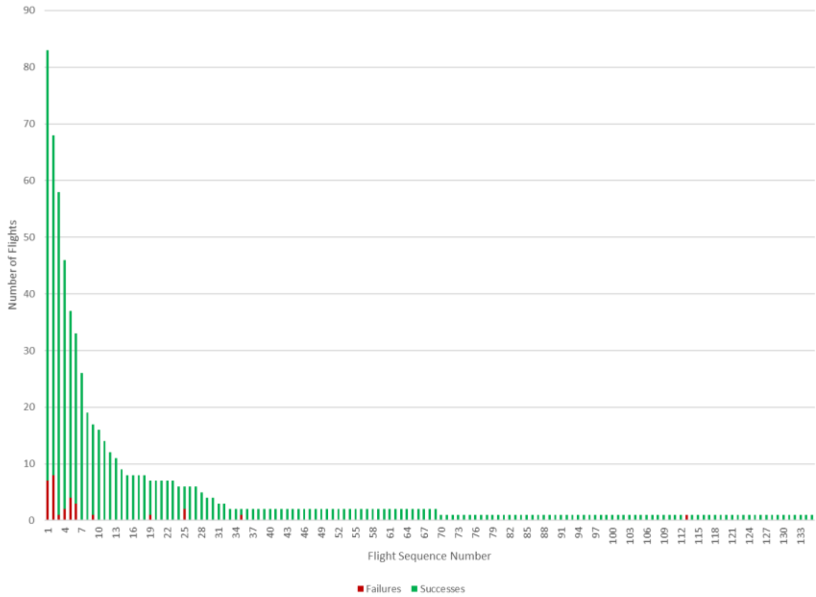
Design Element	Failure Probability per Design Element	Number of Launch Vehicle Design Elements	Total Design Element Failure Probability
Avionics	1.32E-2	1	1.32E-02
1st Stage Liquid Engines	9.85E-3	3	2.93E-02
Solid Propulsion	6.21E-3	2	1.24E-02
Upper Stage Liquid Engines	2.03E-2	2	4.02E-02
Stage Separation	1.36E-2	1	1.36E-02
Fairing Separation	2.01E-2	1	2.01E-02
Thrust Vector Control	1.95E-3	7	1.36E-02
Total			1.34E-01

The values in Table 3 show an estimate of 0.134, or about 1 in 7.5 for the first flight of the new launch vehicle. The estimate is higher than the empirical baseline estimate because the complexity of the vehicle, e.g. the number of engines, is higher than the average launch vehicle.

3.4. Modifying the Baseline Estimate Accounting for an Assurance Program's Effectively Maturing a Launch Vehicle

An effective assurance program can be equivalent to maturing a launch vehicle so that the probability of failure on the first flight is equivalent to the probability of failure after a given number of launches in which identified failures and defects were corrected. Launch vehicle reliability growth to maturity can vary based on how well the launch provider uncovers and corrects issues. Maturity does not mean that failures will not occur, but rather that latent problems in the design have a low probability of failure or random problems can occur during manufacturing, but any higher probability events have been found and corrected. This methodology requires that "maturity" be defined, and in order to do that Figure 2 was developed to show failures and successes as a function of launch sequence number.

Figure 2: Launch Vehicle Successes and Failures by Flight Sequence Number



From Figure 2, failures (in red) are less probable with increasing flights and after 10 flights the failures become more or less random. Table 4 gives the estimated failure probability versus flight number. The estimates in Table 4 are based on no failures occurring. The failure probability estimates range from 1/7 with 0 flights (the baseline estimate) to 1/75 for after 10 flights. The estimates decrease in a smooth manner with a decreasing rate of change.

As an initial estimate, the first flight failure probability for the new launch vehicle can be taken as ranging from the values shown in Table 4 depending on the effectiveness of the assurance program. An average assurance program or possibly a new untested technology would not take any additional credit for finding and correcting issues prior to the first flight which would provide it with an unadjusted first flight failure probability value. An effective assurance program that identifies and corrects all latent failures and defects prior to the first flight can be taken to be equivalent to achieving a failure probability equivalent to having achieved 10 flights. This would result in the first flight failure probability of a new vehicle being equivalent to a mature vehicle with effective identification and correction of manufacturing and operational defects. A value somewhere between the two end points could be judged appropriate based on assessment of the effectiveness of the assurance program and successful past experience with design elements. Justification of the amount of credit taken would be documented in terms of identification of past history of design elements if any, identification of historical failures and how the assurance program has addressed them, additional testing performed, etc. A more detailed assessment would be based using safety case and evidence analysis [2,3].

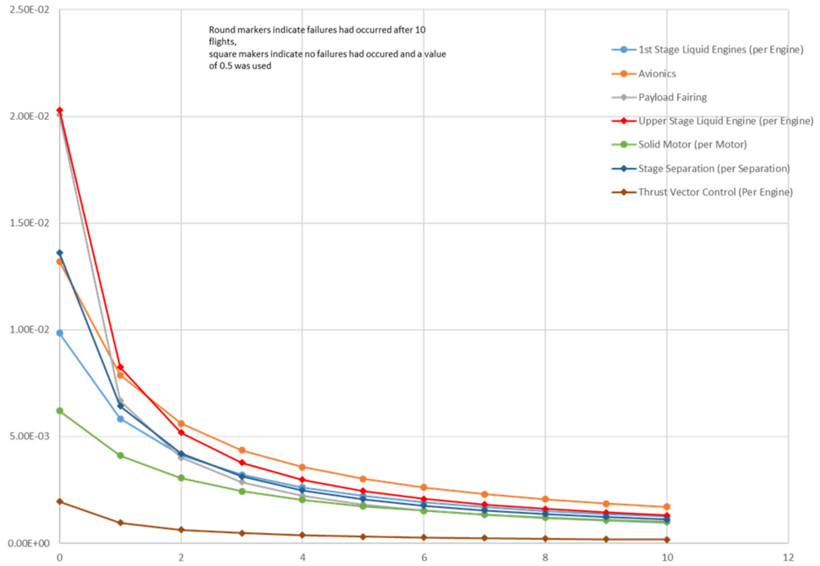
Table 4: Estimated Failure Probability Versus Flight Number

Flights	Estimated Failure Probability	1 in Flights (1 / Failure Probability)
0	0.134	7
1	0.070	14
2	0.048	21
3	0.036	28
4	0.029	35
5	0.024	41
6	0.021	48
7	0.018	55
8	0.016	62
9	0.015	68
10	0.013	75

3.5. Synthesized Probability of Failure by Design Element

The synthesis method just described in the example provides a method of estimating the overall vehicle reliability growth estimate based on a number of launches. Because different design elements may have different assurance approaches and some may be quite rigorous and others less so, the above method can be enhanced to a design element level where results similar to Table 4 are developed for each design element. The same methodology used on the overall vehicle was applied at a design element level. Mature values of 5, 7, or 10 flights were used based on the flight history of the design element. The results of the analysis are provided in Figure 3 and shows the estimated probability of failure by design element for the first 10 flights of a new launch vehicle with and experienced developer.

Figure 3: Probability of Failure Estimate by Design Element



3.6. Example of Synthesizing the Launch Vehicle Estimate Based on Design Elements and Credit for the Assurance Program

As an example of how this methodology can be used, assume that it is determined that the design and assurance program for the new launch vehicle matures some design elements beyond a completely new first flight as in Table 5.

Table 5: Example Assessment of Design Element Assurance Programs for New Launch Vehicle

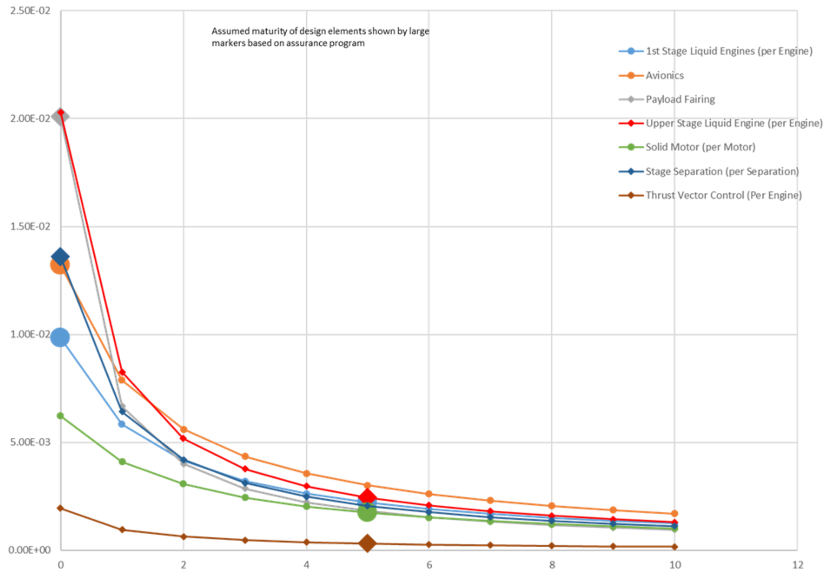
Design Element	Flight Credit	Assumption
1st Stage Liquid Engines	0	New launch vehicle with a new 1st stage engine design. No credit is given for maturity past the first flight.
1st Stage Solid Motors	5	The 4 segment design is the same as used on previous launch vehicles. The single historical design failure was effectively corrected. Credit is given based on the historical success.
2nd Stage Liquid Engines	5	The upper stage engine has a history of success with other launch vehicles as an upper stage engine with one design related failure and numerous successes after the failure occurred.
Thrust Vector Control	5	The TVC for the solid rocket motors and upper stage engines are the same as used in other launch vehicles and has extensive experience and success. For the core stage liquid engines, the TVC is a new design. Credit is given for the solid rocket motors and upper stage
Fairing Separation	0	New launch vehicle with a new fairing design. Several historical failures have occurred. No credit is given for maturity past the first flight.
Stage Separation	0	New launch vehicle with a new separation design. Several historical failures have occurred. No credit is given for maturity past the first flight.
Avionics	0	The software will be unique so no credit is given for maturing the design element past the first flight. Several historical failures have occurred in both hardware and software.

The enlarged markers on Figure 4 show the values that would be used for the first flight equivalent analysis. The results are shown in Table 6. With the additional credit for the assurance program as described, the probability of failure for goes from 0.134 to 0.0898 or a 34 percent improvement. One caution that needs to be mentioned is that new launch vehicles, particularly those with new technologies may have failure modes that have not been experienced before. This should also be taken into account when assigning the level of maturity based on the assurance program for the design elements.

Table 6: Example First Flight Failure Probability with Credit for Assurance Practices

Design Element	Design Element Flight Equivalent Experience Level	Adjusted Total Design Element Failure Probability	Total Adjusted Design Element Failure Probability
Avionics	0	1.32E-02	1.32E-02
1st Stage Liquid Engines	0	9.85E-03	2.93E-02
Solid Propulsion	5	1.74E-03	3.47E-03
Upper Stage Liquid Engines	5	2.45E-03	4.89E-03
Stage Separation	0	1.36E-02	1.36E-02
Fairing Separation	0	2.01E-02	2.01E-02
Thrust Vector Control	5	3.14E-04	8.73E-03
Total			8.98E-02

Figure 4: Example Design Element Maturity with Credit for Assurance Practices



3.7. Bridging to a PRA Model

The method just described provides a much better estimate for early flight failure probability than a mature PRA model, but a PRA model can provide a good mature level failure probability, so finding a way to bridge between the two methods for a consistent program level (i.e. consisting of many flights) failure probability assessment is desirable.

First flight failure probability for an average launch vehicle can be an order of magnitude higher than the same vehicle's estimated mature failure probability, and therefore early flight failure probability would be dominant if no credit is taken for heritage hardware or assurance practices. If credit is given, then the early failure probability would not be as significant a contribution to the overall failure probability.

In order to bridge between the early flight failure probability and PRA estimates, the credit given for assurance practices may be thought of as a derating factor (f) for the early failure probability . For example, in Figure 4, the assurance for the payload fairing is not given any credit so $f = 1$, i.e. it has the early failure probability while the upper stage engines are given 5 flights credit which is about a 0.88 reduction from the baseline no credit case, so f =0.12 This derating factor can then be applied to generally combine the early flight and PRA failure probability using the standard mixture-model formula:

$$p = (1 - f) * p_0 + f p_\varepsilon$$

where p_0 is the PRA estimate and p_ε is the early flight failure probability estimate. Using this equation the early flight failure probability and PRA values are appropriately weighted based on the assessment of the assurance program and hardware and are not double counted. At a point where the early flight failure probability equals the PRA value, f would be 0 and the design would be considered mature.

4. CONCLUSION

New launch vehicles have historically had a significantly higher average failure probability than mature launch vehicles, and PRA analyses do not adequately assess their failure probability. Assurance programs for launch vehicles have an impact on the success or failure probability of launch vehicles. By reviewing historical failures against assurance practices, greater confidence can be had for the first flight of a new vehicle and using the methodology above can translate into a more accurate estimate of first flight failure probability and can be used bridged into an existing PRA model.

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