Design Reliability Comparison for SpaceX Falcon Vehicles

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Introduction

This study by Futron Corporation[1] sought to determine the underlying causes of launch vehicle failures by analyzing the subsystems at fault and establishing an industry average failure rate for each subsystem. An approximate probability of failure for each launch vehicle can then be determined by summing up the chances of failure of all of its subsystems. The approach adopted is similar to that of an Aerospace Corporation study[2] undertaken in 2000, although with more granularity in the propulsion analysis. There are other more detailed methods for calculating a vehicle's design reliability, yet the method presented here provides a useful benchmark by comparing each vehicle to the same industry average failure rates for the major subsystems. This allows for a relative comparison of the inherent simplicity or complexity of a launch system. The actual performance history, the most important measure of a vehicle's reliability, reveals that vehicles have failure rates well above or below what would be expected if every vehicle was as good as the industry average. Absent an actual track record, design reliability gives the only measure of expected performance.

Charts showing the comparative reliability of US launch vehicles are provided in Figures 1 and 2. According to this analysis, the SpaceX Falcon V has the highest level of design reliability when applying the same failure rates as the industry average. The industry-average design reliability for Falcon I is comparable only to the simplest configurations of Delta IV and Atlas V, when no solid boosters are employed.

For launches of US-built vehicles in the last 20 years, problems with the propulsion system caused 52 percent of all failures. Six of the 13 propulsion failures involved liquid engines and the other seven failures involved solid motors. After propulsion, the second most common cause of launch failures was separation events, which were responsible for 28 percent of all failures. Separation failures included staging, payload separation, or fairing separation. The remaining 20 percent of all failures occurred in the avionics or electrical subsystems and at least one failure was blamed on a lightning strike.

Table 1 summarizes the root causes of the 25 launch failures out of the 470 orbital launches of all US-built vehicles from October 1984 through September 2004. A list describing the details of each failure is included as an appendix for further reference.

Table 1: Launch Failures by Subsystem Root Cause of US-Built Expendable Vehicles 1984-2004

Failure Type	Number of Failures	Percent
Liquid Propulsion(Start)	3	12%
Liquid Propulsion (In-flight)	3	12%
Solid Propulsion (Shell)	4	16%
Solid Propulsion (TVC)	3	12%
Stage Separation	6	24%
Fairing Separation	1	4%
Electrical	2	8%
Avionics	2	8%
Other (lightning strike)	1	4%
TOTAL	25	100%

[1] The research underlying this report was sponsored by SpaceX; however, the analysis and conclusions were developed by Futron.
[2] Aerospace Corporation "Space Launch Vehicle Reliability" by I-Shih Chang.

Subsystem Failure Rates

Over the past 20 years, US builders have launched nearly 60 vehicle variants from about a dozen vehicle families. Many families contained similar parts: solid motors for the Pegasus vehicle flew both as Pegasus and Taurus, and the Centaur upper stage flew both on Atlas and Titan variants. US vehicles had between two and four primary stages, and employed a mix of solid and liquid propulsion systems. The Space Shuttle deployed satellites and planetary probes during this period using solid motor upper stages, in addition to its customary three liquid main engines and two solid boosters.

To calculate the total number of liquid engines, solid motors, and other subsystems that flew during this period, we multiplied the number of engines, stages, and solid boosters contained on each variant times the number of launches for each variant. We then subtracted the subsystems that did not get a chance to perform because of a failure earlier in the launch sequence that ended the mission. Table 2 summarizes these totals and divides them into the number of mission failures attributed to each subsystem. This allows us to determine the individual failure rates for the major subsystems of US launch vehicles.

In analyzing liquid and solid propulsion failures, two distinct categories of failure emerge. Liquid propulsion failures occurred either due to a failure in the start sequence or failure later in flight due to insufficient thrust or a premature shutdown. On the other hand, solid rocket motors always started well. Failures there were due either to a breach of the shell or loss of thrust vector control (TVC), with the latter usually arising from a depletion of hydraulic fluid. Solid motor TVC failures have sometimes been ascribed to poor prediction of vehicle dynamics that in turn caused premature depletion of TVC hydraulic fluid. By comparison, liquid-fueled vehicles like SpaceX Falcon tap into the propellant for hydraulic fluid, and therefore cannot deplete fluid prior to end of engine burn. Such a design would not have failed under the same circumstances. No flight of a US-built vehicle in this period experienced a complete mission failure due to the failure of a small strap-on booster to separate. Yet one separation failure resulted in a payload reaching a lower-than-intended orbit.

Table 2: Subsystem Failure Rates for US-Built Vehicles from October 1984 through September 2004

Failure Type	Failures	Total Events	Individual Percent Failure Rate
Liquid Propulsion (Start)	3	1255	0.239%
Liquid Propulsion (In-flight)	3	1255	0.239%
Total Liquid Failure	**6**	**1255**	**0.478%**
Solid Propulsion (Shell)	4	1831 (all solids)	0.218%
Solid Propulsion (TVC)	3	571 (TVC only)	0.525%
Solid Propulsion with TVC (TVC and Shell Failure Modes)	**--**	**--**	**0.743%**
Stage, Booster, and Payload Separations	6	2577	0.233%
Fairing Separation	1	357	0.280%
Small Solid Booster Separations	1*	1165	0.086%
Electrical	2	470	0.426%
Avionics	2	470	0.426%
Other	1	470	0.213%

*Did not result in total mission loss.

Designing for Reliability

Simplicity and redundancy are the keys to high design reliability for any system and launch vehicles are no exception. The greater the number of engines or the greater the number of separation events, the greater the chances that a failure in one of these critical systems can end in mission failure. Given that separation events and engine/motor failures are the cause of approximately 80% of all launch vehicle failures, addressing those subsystems will yield the most significant improvement in reliability.

The chart in Figure 1 compares the relative complexity of current US launch systems by showing the expected failure rate if each vehicle subsystem had a failure rate equal to the US industry average. We calculated the individual failure rate for each subsystem in the flight sequence, and summed them together. All current liquid-fueled vehicles allow the first stage engine to be powered up and checked for problems before release, so we used only the in-flight failure rate for these stages. Passive solid motors that do not have a TVC system can only fail if the shell casing is breached. Therefore, only the shell casing failure rate was used for such motors. For solid motors with a TVC, we used the total failure rate allowing for both a failure in the TVC or the shell casing.

A vehicle with only two stages and one engine per stage has the fewest number of engine burns and staging events. If the first stage uses a liquid engine that can be powered up and tested for anomalies before release, only engine problems that develop later in flight can cause the loss of a payload. Only Falcon I and the simplest configuration of Atlas V and Delta IV (in which no solid boosters are used) meet this criterion. Falcon V's engine-out capability gives Falcon V the best expected design reliability since a failure would require two out of five engines to fail in flight. Figure 2 shows the expected failure rates when all historical failures are considered. In this case, the same failure rate applies to all vehicles for avionics and electrical failures.

Figure 1: Expected Failure Rates Due to Propulsion and Separation Events Based on the Historical Average

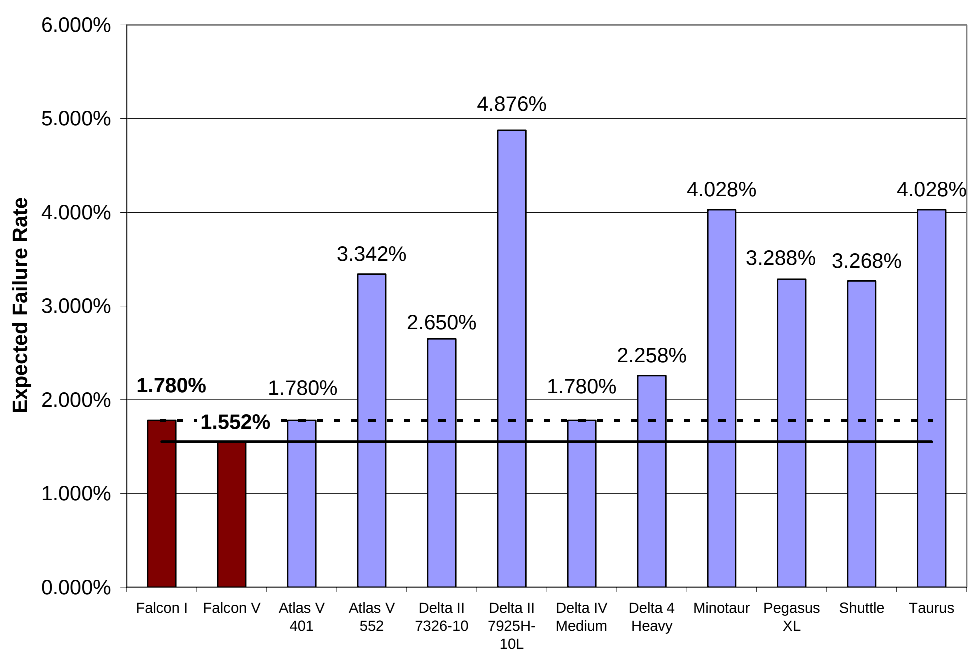
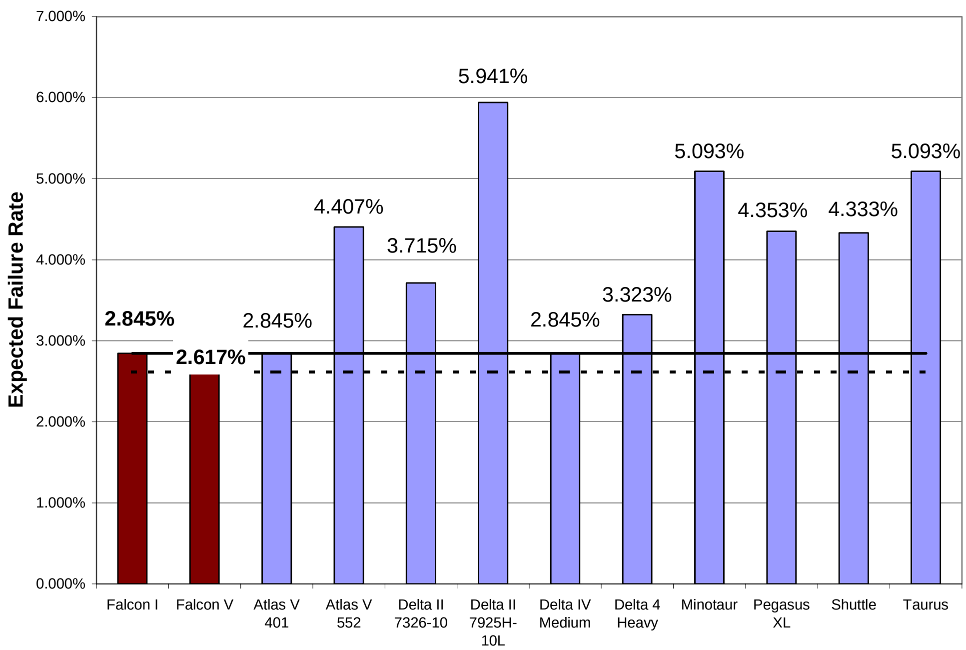


Figure 2: Expected Failure Rates Due to All Causes Based on Historical Average Subsystem Failures



List of Failures

Date	Vehicle	Failure Type	Failure Notes
8/28/1985	Titan 34D	Liquid (In-flight)	A propellant feed system failure
1/28/1986	Challenger	Solid (Shell)	Hot gases burned through an O-ring seal
4/18/1986	Titan 34D	Solid (Shell)	Hot gases burned through insulation in the casing
5/3/1986	Delta 3914	Electrical	An electrical fault caused early main engine shutdown
3/26/1987	Atlas G	Other	Struck by lightning 59 seconds into flight
9/2/1988	Titan 34D	Liquid (In-flight)	Transtage burn failure due to broken propellant feed lines
3/14/1990	Titan 3	Stage Separation	Second stage did not separate from payload
4/18/1991	Atlas 1	Liquid (Start)	One of two Centaur engine did not fire and stage tumbled
7/17/1991	Pegasus 1/HAPS	Stage Separation	Vehicle veered off course following first stage separation; failure attributed to a failure in the separation pyrotechnics
8/22/1992	Atlas 1	Liquid (Start)	Upper stage failed to reach full thrust due to a frozen fuel pump
3/25/1993	Atlas 1	Liquid (In-flight)	First stage powered down to 65% 24 seconds into flight
8/2/1993	Titan 4A	Solid (Shell)	Hot gases burned through the casing
6/27/1994	Pegasus XL	Avionics	Incorrect dynamic modeling caused loss of control
6/22/1995	Pegasus XL	Stage Separation	Incorrect assembly prevented the interstage ring from separating
8/15/1995	Athena 1	Solid (TVC)	Hydraulic fluid vented onto the thrust vector controller
10/23/1995	Conestoga 1620	Solid (TVC)	Thrust vector control system depleted hydraulic fluid
11/4/1996	Pegasus XL	Stage Separation	Payload failed to separate from third stage due to failure of pyrotechnic system (pyrotechnics did not fire)
1/17/1997	Delta 2 7925-10	Solid (Shell)	A solid booster ruptured due to damage during ground handling
8/12/1998	Titan 4A/Centaur	Electrical	Damaged wire harness resulted in intermittent power to avionics
8/26/1998	Delta 3	Solid (TVC)	Depleted hydraulic fluid compensating for vehicle oscillations
4/9/1999	Titan 4B/IUS	Stage Separation	Separation of the first motor in the IUS upper stage damaged the second motor, causing improper firing.
4/27/1999	Athena 2	Fairing Separation	Fairing remained attached due to incorrect separation sequence
4/30/1999	Titan 4B/Centaur	Avionics	Wrong value in software caused upper stage to fire incorrectly
5/4/1999	Delta 3	Liquid (Start)	Rupture in combustion chamber joint at start of second firing
9/21/2001	Taurus 1	Stage Separation	First and second stages did not separate properly