Reliability Drivers for Advanced Space Vehicles

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III. Nomenclature

DoD	Department of Defense
ELV	Expendable Launch Vehicle
GA	General Aviation
ISTP	Integrated Space Transportation Plan
LEO	Low Earth Orbit
LOC	Loss of Crew
LOV	Loss of Vehicle
NASA	National Aeronautics and Space Administration
OSMA	Office of Safety and Mission Assurance
PFS	Propellant Feed System
PSS	Propellant Storage System
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
SLI	Space Launch Initiative
STAS	Space Transportation Architecture Studies
STS	Space Transportation System
TVC	Thrust Vector Control

1. Introduction

This research seeks to gain a quantitative understanding of launch vehicle reliability by identifying major launch vehicle subsystems that contribute the most to catastrophic mission failures and to estimate the failure rates associated with each. By identifying the launch vehicle subsystems that historically contribute the most to launch vehicle failure, it may be possible to plan a future course of subsystems research that will benefit reliability and safety of future launch systems. It may also become possible to optimally distribute the limited resources for improving subsystem reliability to those that can contribute the most to overall launch vehicle reliability. In addition, the quantitative reliability data gathered may be used to develop more accurate conceptual estimates of future reusable launch vehicle safety and reliability.

The quantitative subsystem reliability data for this report have been calculated by reviewing historical ELV and STS failures from worldwide and US launch vehicles as well as some US launch vehicle subsystem test data. Many of these failures have previously been categorized according to their root cause (by subsystem). Using this historical data, estimates have been made of the expected catastrophic failure rates of 10 key launch vehicle subsystems for worldwide and US-only launch systems. For comparison, the subsystems-level launch vehicle expected failure rates have been compared to expected failure rates from Complex General Aviation aircraft.

2. Background

2.1 Research Context

In the fall of 1999, the United States National Aeronautics and Space Administration (NASA) devised a long-range investment strategy called the Integrated Space Transportation Plan (ISTP). The ISTP defines a comprehensive investment strategy for all of NASA's diverse space transportation missions. The objective of the ISTP is to improve space transportation capabilities for both cargo and crew missions. This is to be achieved by developing and applying risk-reducing technologies to create a safer and significantly more reliable space transportation system. This new launch system is envisioned to be owned and operated by private enterprises and having NASA as one of its customers.[10]

The Integrated Space Transportation Plan (ISTP) is based on earlier Space Transportation Architecture Studies (STAS).[10] The STAS studies were separate efforts that were undertaken by NASA, the Department of Defense (DoD), and aerospace industry. These studies defined a number of objectives to be achieved in next few decades by the aerospace industries and the government. At the heart of the ISTP agenda sits two major tasks. They are; 1) significantly increasing the reliability and safety of the next generation launch vehicles, and 2) significantly reducing the cost of accessing low earth orbit with the ultimate goals of proliferation of commercial launch capabilities and providing growth paths for human space exploration.[3,10]

This effort to dramatically increase reliability and safety and lower the cost of space transportation is headed by NASA's Marshall Space Flight Center in Huntsville, Alabama. Under its leadership, a program called the Space Launch Initiative (SLI) has been provided with $290 million in 2001. For next five years, its budget is projected to be $4.5 billion. Its program phases and major milestone are shown on Figure 2.1.[10]

The objective of the Space Launch Initiative (SLI) is to encourage industry, academia and others to propose technologies, experiments and other risk-reduction activities over the next five years for the 2nd Generation Reusable Launch Vehicle (RLV) Program. It is NASA's hope to start the full-scale development of a reusable launch system by the year 2005, with achieving flight operation status around year 2010.[10]

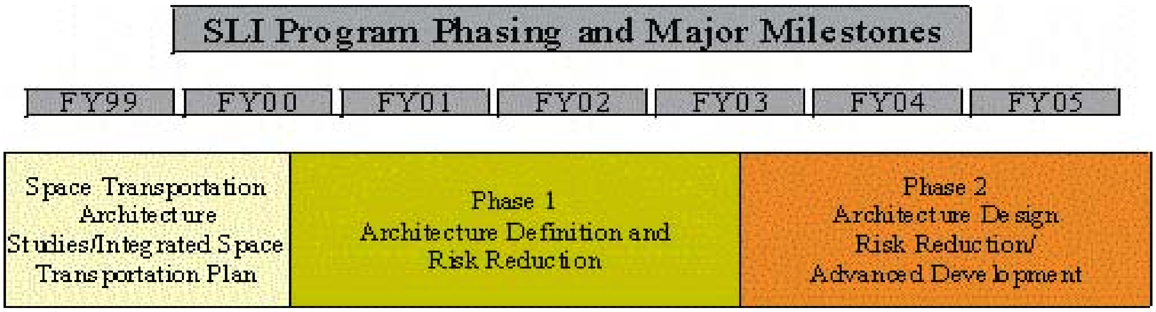

Figure 2.1: SLI Program Phasing and Major Milestones[10]

With the subsequent generations of launch vehicles, NASA aims to achieve orders of magnitude improvements in reliability and safety compared to current launch vehicle families. Therefore, by the time 3^{rd} or 4^{th} generation Reusable Launch Vehicles (RLV) become operational, access to space would be as routine, affordable, reliable and safe as current air transportation today.

America's Space Shuttle, which has been in service for over 20 years, is defined as 1^{st} Generation Reusable Launch Vehicle. Current 1^{st} Generation RLV has Loss of Crew (LOC) rate of no worse than 1 in 100 missions (current estimates are around 1 in 250), delivery cost to Low Earth Orbit (LEO) of approximately $10,000 per pound, needs 5 months to prepare for re-flight, and the total fleet flies less than 10 times a year.[3,10]

The 2^{nd} Generation RLV envisioned by SLI aims to be operational around year 2010. Its operations cost to LEO is projected to be approximately $1,000 per pound. It will require a ground crew of only hundreds of people and will need only weeks to prepare for re-flight. In the safety and reliability aspect, it is to achieve an ascent mission Loss of Vehicle (LOV) risk of 1 in approximately 1,000 missions and achieve an ascent mission Loss of Crew (LOC) risk of 1 in approximately 10,000 missions.[3,10]

The 3^{rd} Generation RLV defined by ISTP is projected to come into service around year 2025. With this vehicle, NASA plans to reduce delivery cost to LEO to hundreds of dollars per pound, reduce ground crew to tens of people and reduce ground preparation for re-flight to days instead of weeks or months. This 3^{rd} Generation RLV fleet will fly hundreds time a year. In the safety and reliability aspect, it is to achieve crew safety design goal of 1 in 1,000,000 missions between Loss of Crew (LOC).[3,10]

There is also a plan for developing a 4^{th} generation RLV system to be introduced around 2040, which would achieve safety equal to that of the current air transportation system[3] (current air transportation mission Loss of Crew (LOC) event on a flight is 1 in approximately 2,102,500 per flight).[5]

2.2 Reliability Analysis

To successfully improve the reliability, safety and affordability for the next generations of launch vehicles, study of current launch vehicle family reliability is essential. The identification of the current levels of reliability and safety will create a technological benchmark that will aid future technology development and certification standard development.

Of the three attributes of future launch vehicle envisioned by ISTP: reliability, safety and affordability, reliability is the most important factor. Reliability is major driver for both cost and risk. The results of reliability analyses are direct inputs to the cost and the safety analyses.

For the launch vehicle industry, reliability analysis has been historically inadequate due to the industry tradition and nature of the launch vehicles. Initially, there was interest in quantitative risk assessment for the Apollo programs but the effort was abandoned early on. Since then and for at least 40 years, the design, development and operation of liquid rockets have been based on specification limits, safety factors, proof tests, acceptance tests, qualification demonstrations and a test/fail/fix approach. The traditional aerospace vehicle design process has emphasized "design conservatively, test extensively, determine cause of problems and fix" and tried to mitigate the remaining risks. When some formal reliability analysis was conducted, the lessons learned from one program were not exchanged to the next program.[4-6]

The nature of the launch vehicle industry also greatly contributes to the lack of meaningful reliability data. Other industries such as aircraft and automobile industries have reliability engineering methods fairly well established due to the maturity of these industries. These industries deal with products that have high production rates and have large pool of good comparative data of many generations of a single system. Unlike such systems as aircraft and automobile, most rockets are expendable. Reusable launch vehicles are few in numbers (STS is partially reusability) and have low flight rate. In addition, many rockets are unique, therefore not necessarily mass production vehicles like aircraft and automobiles. Finally, the commercial launch vehicle data are often not available to the public and often seen as proprietary information to the company.[4-6]

2.3 Solution Approach

In this research, the reliability data for system-level failures, subsystem-level failures, and liquid-fuel propulsion engine subsystem failures have been gathered from the ELV and STS catastrophic failure databases that have been published in various open sources. The reliability data generated for the US liquid-fuel propulsion systems have been further studied using a study done by the Safety, Reliability, Maintainability and Quality Assurance Office of NASA Headquarters in early 1990's.[11,12]

3. Data Sources

3.1 Launch Vehicle Data

3.1.1 Launch Vehicle and Subsystem Data

At the vehicle-level, Hopkins, Hopkins, and Isakowitz have published mission failure data for a range of historical launch systems (Ref. 8). For this study, the vehicle-level reliability estimates are based on historical launch data of 11 launch vehicles that were operational for some time up to the year 1999. Of the total 11 launch systems, 6 vehicles are U.S. vehicles and one representative was chosen from each of five other nations. The names, total launches, number of successful missions, partially successful missions, and failed missions for each launch system used in this study are listed in Table 3.1.[8]

Table 3.1:Launch History[8]

Launch Vehicle Name	Nation	Total Launches	Total Mission Success	Total Partial Success*	Total Mission Failures
Ariane	Europe	117	108	1	8
Athena	United States	5	3	0	2
Atlas	United States	305	265	0	40
Delta	United States	271	253	5	13
H-Series	Japan	30	28	1	1
Long March	China	57	48	3	6
Pegasus	United States	27	22	2	3
Proton	Russia	284	252	2	30
Space Shuttle	United States	94	91	2	1
Titan	United States	203	184	4	15
Tsiklon	Ukraine	249	241	1	7

*The Number of Partial Success refers to mission failure that did not result in catastrophic failure of the launch vehicle

The worldwide and US catastrophic failures were further distributed by subsystem using data published in References 1, 8, and 11. These results will be presented in chapter 5.

3.1.2 Liquid Fuel Propulsion Subsystem Data

The quantitative reliability data collected specifically for liquid-fuel propulsion subsystems are based on the data gathered by McFadden and Shen during 1988 and 1989 for a study sponsored by the Safety, Reliability, Maintainability and Quality Assurance Office of NASA Headquarters as well as the launch data of vehicles listed in Table 3.1. McFadden and Shen's study based its analysis on the liquid-fuel propulsion systems used in the family of Atlas, Delta, Saturn, Titan and Space Shuttle launchers from the beginning of the space program to the year 1989. NASA Marshall Flight Center compiled a launch history database covering all US liquid-fuel launch vehicles in use as well as test firing data, and this is incorporated. The complete lists of the launch vehicles covered by this study are listed on Table 3.2.[12]

Table 3.2:US Liquid-fuel Launch Vehicle Database[12]

Atlas/Centaur	Delta	Titan I
Atlas D	Space Shuttle	Titan II
Atlas E	Saturn I	Titan III
Atlas F	Saturn IB	Atlas G
Atlas H	Saturn V	
Atlas SLV	Titan 34D	

Along with the launch systems listed on Table 3.2, liquid-fuel upper stages commonly used with these launchers such as Centaur have been included in the database of US liquid-fuel propulsion subsystems. The engine model number and its corresponding manufacturer and launch vehicle are listed on Table 3.3.[12]

Table 3.3:US Liquid-fuel Engine List[12]

Engine Model Number	Manufacturer	Launch Vehicle
LR87-AJ-11	Aerojet	Titan
LR91-AJ-11	Aerojet	Titan
LR-87-AJ-S	Aerojet	Titan
LR-91-AJ-5	Aerojet	Titan
YLR-89-NA7	Rocketdyne	Atlas
YLR-105-NA7	Rocketdyne	Atlas
LR-89-NA5	Rocketdyne	Atlas
LR-105-NA5	Rocketdyne	Atlas
RL10A-3	Pratt & Whitney	Atlas/Centaur
F-1	Rocketdyne	Saturn
J-2	Rocketdyne	Saturn
H-1	Rocketdyne	Saturn
AJ-10-118K	Aerojet	Delta
RS-27	Rocketdyne	Delta
RS-27A	Rocketdyne	Delta
TR-201	TRW	Delta
SSME	Rocketdyne	Space Shuttle

The data gathered were based on a composite historical launches comprise of 1438 total launches, of which 1195 have been considered successful by the NASA or USAF and 243 have been considered unsuccessful.[12] Using these data, McFadden and Shen determined the contribution of major US liquid-fuel propulsion components on propulsion subsystem failure. The percent contributions to propulsion failures are listed on Table 3.4.

Table 3.4: Component Contribution to US Liquid-fuel Propulsion Failure[12]

Propulsion Subsystems	Percent contribution to failure
Fuel feed and control	15.0%
Oxidizer feed and control	7.5%
Combustion chamber	4.2%
Nozzle	0.8%
Pressurization	10.0%
Lubrication	1.7%
Electrical Control	8.3%
Hydraulic/pneumatic control	16.7%
Thrust vector control	0.8%
Engine structure	0.8%
Others	34.2%

3.2 Complex General Aviation Aircraft Data

In order to compare the launch vehicle reliability to current air transportation systems in use, the reliability of the launch vehicle subsystems are compared with reliability of Complex General Aviation (GA) aircraft subsystems. NASA Langley Research Center's Office of Safety and Mission Assurance (OSMA) gathered and generated the reliability data of Complex General Aviation (GA) Aircraft subsystems in 2001. Pettit and Turnbull define "Complex GA Aircraft" as any fixed wing aircraft operating under FAR Part 91, 125, 135 or 137, excluding experimental aircraft and gliders.[13,14] Their reliability estimates are based on operation of the Complex GA for six hours flight with cruise speed of 160 knots and a range of 700nm. The Complex GA is defined as single piloted aircraft which allows 3 other passenger, equipped with light-single engine piston aircraft with near all-weather capability. It is equipped with retractable landing gear, flaps, and constant-speed propeller.[13,14] The reliability of the Complex GA Aircraft system is estimated by Weibull distribution.

The subsystem definitions and classifications used in Pettit and Turnbull's Complex GA system analysis are described in detail in Appendix II. Table 3.5 indicates the reliability for each subsystem ranked from most unreliable to the most reliable subsystems.

Table 3.5:Reliability for Complex GA Subsystems[13]

Rank	Subsystems	Average Reliability
1	cockpit instrument	0.97600
2	flight control	0.98475
3	ground control	0.99598
4	structures	0.99940
5	non-engine propulsion	0.99988
6	engine	0.99997
7	electrical	0.99997

4. Launch Vehicle Subsystems Definition

For this reliability study, the launch vehicle was subdivided into number of subsystems, and the failure data was acquired for each of these subsystems and corresponding reliability was estimated. In this study, 11 subsystems of the launch vehicle are identified, including "Design". Each of these subsystems is presented below with definition of each subsystem. Note that the Propulsion subsystem is shown to be further divided into Engine and Propellant Feed System components.

<u>Attitude Control System</u> consists of reaction control system (RCS), thrust vector control (TVC) system, electronics and computers necessary to control them. The thrust vector control (TVC) system classified in this subsystem definition includes, actuators, directly associated hydraulic and electronic controllers, but it does not include gimbals allowing the engine to move for thrust vector control. The TVC system also consist of systems to perform thrust vector control via secondary injection methods such as gas injection using inert stored gas, or liquid injection in the flow method.[2,3,8,9]

<u>Aviation and Flight Control Systems</u> consists of any component that controls the launch vehicle's attitude, heading, and altitude or systems that changes the aerodynamic characteristics of the launch vehicles in flight. This subsystem consists of the guidance system, navigation system, communication and tracking systems, gyro and flight-control computers. It does not include the hydraulic system used to physically change the aerodynamic characteristics of the launch vehicles in flight and computer codes for the computer system.[2,3,8,9]

<u>Design of Launch Vehicle</u> is not really a subsystem of the launch vehicle, but it is an aspect that has contributed to the catastrophic failure of the launch vehicle. An example of catastrophic vehicle failure contributed to improper design is June 27, 1994 launch of the Pegasus (US) vehicle. The mission resulted in catastrophic failure of the vehicle and the fault was traced to improper aerodynamics model used in control system autopilot design.[8]

<u>Engine (first part of "Propulsion")</u> consists of one or more thrust chambers and all the lines to the thrust chambers, as well as computer systems to directly control it. The engine subsystem classification also include feed mechanism to force the propellants from the

tanks into thrust chamber, power source for the feed mechanism, a structure to transmit the thrust force generated by the engine. The thrust chamber is composed of propellant injectors and feed manifolds, igniter, combustion chamber, exhaust nozzle and structural cooling systems. The engine subsystem does not include thrust vector control system nor computer codes for the computer system.[2,3,8,9]

Electrical System defines any components involved in source, distribution and conversion of electrical power throughout the launch vehicle.[2,3,8,9]

Hydraulic System defines components used for engine gimbals and valves control, aerodynamic surface controls and landing gear control.[2,3,8,9]

Payload Fairing subsystem consists of payload fairing or payload bay structure, payload doors and hardware, actuators and computer systems to control these hardware. It excludes the mission payload itself, which would not be considered a part of the launch vehicle as well as computer codes for the computer system hardware.[2,3,8,9]

Propellant Feed System (second part of "Propulsion") consists of pump pressure feed system, all the feed lines and other components required for propellant handling and the flow control components. The pump pressure feed system consists of two major components, the pump and the pump driver. Other propellant feed system consists of on/off valves, directional flow or check valves to prevent back flow of propellant into the gas tank, relief valves or relief burst diaphragms to prevent tank from over pressurization, isolation valves to control flow to redundant subsystems, pressure and temperature transducers, sensors to detect leak of hazardous vapor, and computers necessary to control these hardware. But it does not include the computer codes.[2,3,8,9]

Propellant Storage System consists of propellant-tank structure and filters to prevent particulate contaminants from entering the propulsion system and propellant expulsion assembly for propulsion system for those engines design for low gravity environment and tank pressurization systems to maintain the propellant tanks in its desired pressure. The propellant-tank structure is composed of pressure vessel, the structural attachments to the launch vehicle, propellant slosh baffles, and thermal protection systems.[2,3,8,9]

Software subsystem consists of computer codes design to control various components of the launch vehicle.[8]

Structure subsystem consists of any component that is essential to the structural integrity of the launch vehicle. All the vehicle structure used for supporting all the vehicle components, wings, tail group and body are included. But it excludes payload structures, propellant storage structures, as well as environmental protection system such as thermal protection system.[2,3,8,9]

5. Data Analysis Method

Due to the nature of the historical launch vehicle failure database, the common reliability analysis methods such as Poisson, Weibull or Normal distribution could not be applied. These traditional reliability analysis methods require significant historical data of a single system or generations of single system throughout its repeated use. This depth of data is not available for launch vehicles. Therefore the reliability of the previously defined launch vehicle subsystems are herein calculated by simple ratios of historical catastrophic launch vehicle failure data. Such reliability study has advantage of being historically-based and therefore avoids the criticism that reliability analysis did not consider both design and operational failure.[11]

First, a basic vehicle-level reliability estimate was generated from the pool of 11 liquid-fuel propulsion launch vehicles from 6 different nations (Table 3.1). It includes 1642 launches and 1495 of them are considered successful missions. 126 of them were considered to be catastrophic mission failures due the failure of launch vehicle subsystems (there were also 21 partial mission successes which did not result in catastrophic failure).[8] The average reliability, R, of these launch vehicles was calculated by following equation (1), and determined to be about 0.9233. Thus historically, the chance of a successful or partially successful launch worldwide has been 92.33%. Note that this averaging approach ignores any maturation effects that may be present in a given launch vehicle family (i.e. increasing reliability over time is not accounted for).

$$R = 1 - \frac{\text{Number of Catastrophic Failures}}{\text{Number of Total Launches}} \tag{1}$$

A US vehicle-level reliability estimate was also generated using just the 6 launch vehicles from United States in Table 3.1. It includes 905 launches and 818 of them have been considered successful launches and 74 of them have been considered to be catastrophic mission failures due to the failures of the launch vehicle subsystems (there were also 13 partial mission successes which did not result in catastrophic failure).[8] The average reliability of these launch vehicles is about 0.9182 or 91.82%. This is slightly less than the worldwide average.

In order to determine how the failures are distributed among the subsystems, individual failure ratios for each subsystem from chapter 4 were calculated. For the propulsion subsystem, the failure ratios have been further apportioned to engine and propellant feed system (PFS) sub-components due to the availability of more detailed data available on historical failures resulting from propulsion subsystem. It is important to point out, of the 126 worldwide and 74 US catastrophic launch failures of Table 3.1, not all of these failures can be traced back to a single subsystem. Therefore, only those catastrophic failures with a single identifiable subsystem cause have been included in the calculation of the failure ratios (89 worldwide and 53 for the US-only analysis).

The failure ratio has been denoted as ß. The major subsystem failure ratios; $ß_{avionic/fc}$, $ß_{ATC}$, $ß_{design}$, $ß_{electrical}$, $ß_{propulsion}$, $ß_{hydraulic}$, $ß_{payload}$, $ß_{propellant}$, $ß_{software}$, $ß_{structure}$ have been calculated by following equation;[11]

$$ß_{subsystem} = \frac{\text{number of subsystem failure leading to catastrophic mission failure}}{\text{total number of launch vehicle failure leading to catastrophic mission failure}} \quad (2)$$

For example, the number of worldwide catastrophic launch failures due to an attitude control subsystem failure was 5 out of 89 identifiable failures. β_{ATC} is therefore 0.056 or 5.6%.

The failure ratios of the sub-component within the propulsion subsystem ($ß_{engine}$ and $ß_{PFS}$) are calculated by;[11]

$$ß_{sub-component} = \frac{\text{number of sub - component failure leading to catastrophic mission failure}}{\text{number of subsystem failure leading to catastrophic mission failure}} \quad (3)$$

Figure 5.1 represents the failure ratios of worldwide liquid-fuel launch vehicles and Figure 5.2 represents the failure ratios of US liquid-fuel launch vehicles distributed among the major subsystems.

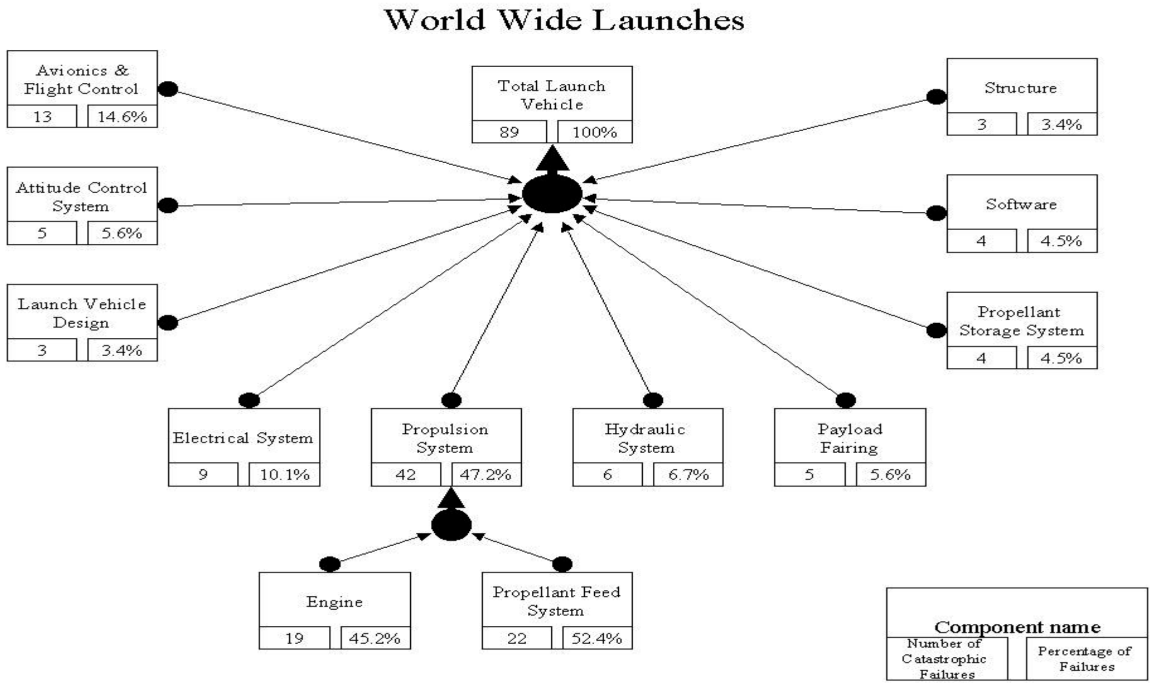

Figure 5.1:Historical Failure Ratios of Worldwide Launch records

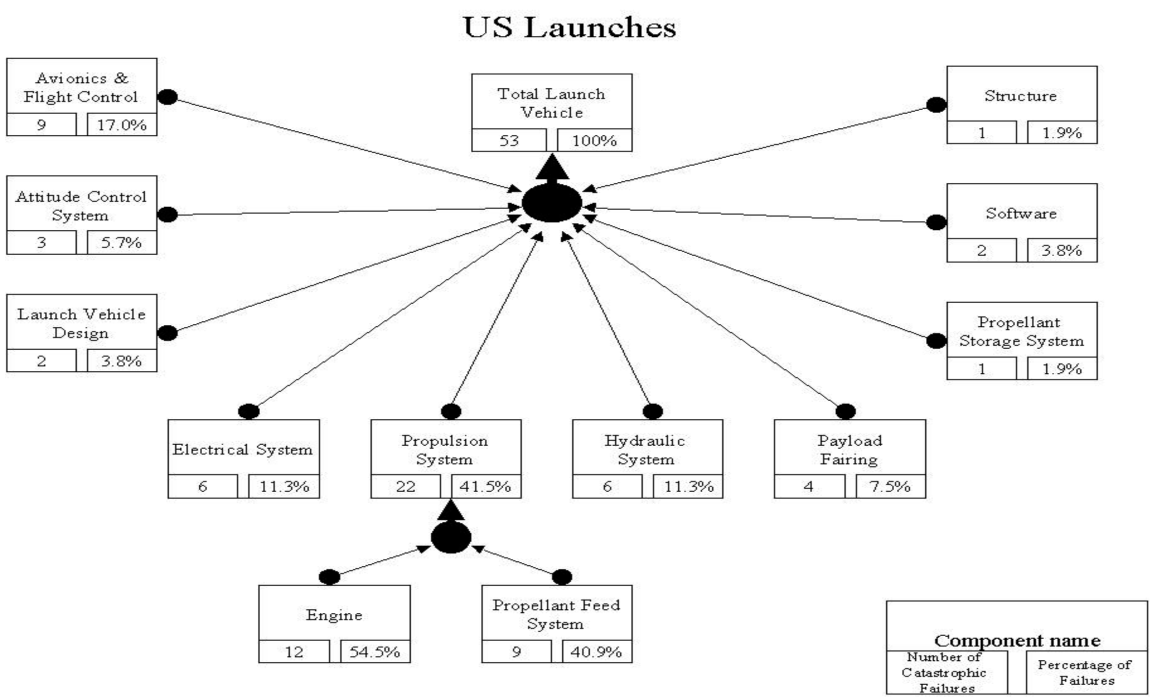

Figure 5.2:Historical Failure Ratios of US Launch records

At this point, its important to point out that some of the failures of the propulsion subsystem could not be categorized into either engine sub-component or propellant feed system (PFS) sub-component. The propulsion failures that could not be identified have been counted in propulsion subsystem failure ratio but not in either the engine or the propellant feed system (PFS) sub-component failure ratios. For example, in the worldwide propulsion subsystems, there were 42 catastrophic failures recorded, but only 19 were identified as the engine sub-component and 22 as the PFS sub-component. The remaining 1 failure could not be classified as belonging to either. This is the reason why the numbers of engine and PFS sub-component failures do not add up to propellant subsystem failure numbers.

Once the failure ratios were determined, the subsystem or sub-component reliability was then calculated by following equation;[11]

$$R_{subsystem-subcomponent} = R_{system}^{B_{subsytem-subcomponent}} \tag{4}$$

where R_{system} is the reliability of the system that is one level above the subsystem in the calculation. For example, for propulsion subsystem, R_{system} is the reliability of the launch vehicle itself (0.9233 worldwide or 0.9182 for US-only) and for engine sub-component, R_{system} is the reliability of the respective propulsion subsystem. Thus, the reliability of the US-only Engine sub-component of the Propulsion subsystem is calculated in following way;

$$0.9809_{engine} = \left(0.9652_{propulsion}\right)^{\frac{12}{22}(\text{ß}_{\text{engine to propulsion}})} \tag{5}$$

And the expected failure rate per flight is calculated by following equation;

$$FailureRate = 1 - R \tag{6}$$

Use of eqn. (4) ensures that the product of all subsystem reliabilities is equal to the overall vehicle reliability.

6. Results

6.1 Launch System Reliability

The failure rates of the liquid-fuel propulsion launch vehicle's subsystems are shown in Table 6.1. These reliability data are based on accounting for all the launch vehicles around the world that are in the database and using equations (4) and (6). They are ranked from subsystems with highest failure rates to lowest failure rates. As expected, the propulsion systems (Propellant Feed System and Engine subsystems) dominate the launch vehicle failures.

Table 6.1: Failure rates of Liquid-fuel Propulsion Launch Vehicles

Ranks	Launch Vehicle Components	Average Failure Rates
1	Propellant Feed System	0.0195
2	Engine	0.0169
3	Avionics and Flight Control System*	0.0116
4	Electrical System	0.0080
5	Hydraulic System	0.0054
6	Payload Fairing	0.0045
6	Attitude Control System	0.0045
7	Software	0.0036
7	Propellant Storage System	0.0036
8	Structure	0.0027
8	Design	0.0027

* e.g. $R_{avionics} = 1 - [0.9233]^{\frac{12}{89}}$

In the aerospace industry, the experiences and knowledge gathered from one generation of launch vehicle to another is shared very little with other nations. This is characteristic of any other technology intensive field, but for the launch vehicle field, it is even more true due to the political consideration of this technology. Therefore inclusion of failure rates of launch vehicles around the world in a single "world" database and generating reliability data from that is not the most desirable due to different approach in technology and different levels of technology maturity. Ideally, the failure rates of the launch systems would be divided into launch systems corresponding to each respective nation. Due to very limited numbers of space launches and lack of data, it is difficult to generate meaningful nation-specific reliability data except for US launch systems. Therefore, the database has been partitioned to include only the US liquid-fuel propulsion launch systems. Using this US-only database (Figure 5.1), the failure rates have been generated and are listed in Table 6.2.

Table 6.2: Failure Rates of US Liquid-fuel Propulsion Launch Vehicles

Ranks	Launch Vehicle Components	Average Failure Rates
1	Engine	0.0191
2	Propellant Feed System	0.0144
2	Avionics and Flight Control System	0.0144
3	Electrical System	0.0096
3	Hydraulic System	0.0096
4	Payload Fairing	0.0064
5	Attitude Control System	0.0048
6	Software	0.0032
6	Design	0.0032
7	Propellant Storage System	0.0016
7	Structure	0.0016

* e.g. $R_{electrical} = 1 - [0.9182]^{\frac{6}{53}}$

The US-only failure rate ranking is relatively similar to the worldwide failure rate ranking. Both US database and worldwide database indicate the propulsion subsystems (Propellant Feed System and Engine) dominate the launch vehicle catastrophic failures during vehicle operations. Avionics/Flight Control System is the next most critical subsystem in both cases.

Table 6.3: Overall Launch Vehicle Failure Rates

Launch Vehicle Name	Nations	Average Failure Rates
Ariane	Europe	0.0684
Athena	United States	0.4000
Atlas	United States	0.1311
Delta	United States	0.0480
H-Series	Japan	0.0333
Long March	China	0.1053
Pegasus	United States	0.1111
Proton	Russia	0.1056
Space Shuttle	United States	0.0106
Titan	United States	0.0739
Tsiklon	Ukraine	0.0281

Using the database from Ref. 8, it is possible to estimate the overall failure rates for different launch vehicle families at the vehicle-level. Table 6.3 shows the names of the launch vehicles and countries of origin and the failure rates of each of the vehicles. The system-level failure rate is represented as the number of catastrophic mission failures divided by total number of launches. These data indicate the safest launch vehicle of those 11 considered has been Space Shuttle with only 1 catastrophic failure in 94 launches through 1999.

6.2 Reliability Comparison with Complex General Aviation Aircraft

The reliability of vehicle subsystem of worldwide and US launch vehicles have been compared to vehicle subsystem reliability of the current complex GA aircraft and ranked from most unreliable to most reliable. The data are shown in Table 6.4.

Table 6.4: Reliability Comparison of Worldwide, US Launch Vehicles to GA Aircraft

	Worldwide Database	Failure rate	US Database	Failure rate	Complex General Aviation	Failure rate
1	▪ PFS	0.0195	▪ Engine	0.0191	▪ cockpit instrument	0.02400
2	▪ Engine	0.0169	▪ PFS ▪ Avionics/FC	0.0144	▪ flight control	0.01525
3	▪ Avionics/FC	0.0116	▪ Electrical ▪ Hydraulic	0.0096	▪ ground control	0.00402
4	▪ Electrical	0.0080	▪ Payload Fairing	0.0064	▪ structures	0.00060
5	▪ Hydraulic	0.0054	▪ ACS	0.0048	▪ non-engine propulsion	0.00012
6	▪ Payload Fairing ▪ ACS	0.0045	▪ Software ▪ Design	0.0032	▪ engine ▪ electrical	0.00003
7	▪ Software ▪ Propellant Storage	0.0036	▪ Propellant Storage ▪ Structure	0.0016		
8	▪ Structure ▪ Design	0.0027				

This comparison shows sharp contrast between reliability of launch vehicle subsystem and complex GA aircraft. <u>For launch system, the propulsion subsystem remains to be the most unreliable subsystem, yet for complex GA aircraft, the propulsion subsystem is one of the most reliable.</u> It also shows the reliability of the Avionics and Flight Control System subsystem for both the launch system and the complex GA aircraft are similar (0.0116 to 0.01525 catastrophic failures per flight).

7. Conclusion and Future Research

The reliability assessment of historical ELV and STS launch vehicle systems has shown that the subsystems that would need significant improvement in reliability are propulsion and avionics/flight control subsystems. These systems have historically contributed the most to the catastrophic failure of the launch vehicles.

Along with designing safer propulsion system and avionics/flight control systems, reliability must be fully integrated into design process from the beginning of the system development though-out its entire lifetime of operation. This approach to reliability management will ensure a space transportation infrastructure that can encourage the proliferation of commercial launch capabilities and provide solid foundation for human space exploration.

Future technology investment strategies aimed at improving these systems through harnessing new technology and more integrated and safety conscience vehicle design will be crucial to achieving NASA's goal of creating a space transportation system that is as reliable and safe as current air transportation systems. Orders of magnitude improvement over historical launch reliability (calculated to be only 0.9182 for US launch vehicles through 1999) will be necessary for NASA to achieve its future RLV reliability goals.

The present research relied heavily on expendable launch vehicle failures to estimate subsystem reliability. This was due to the very limited availability of statistically valid data corresponding to reusable launch vehicles. The space shuttle was the only partially reusable launch vehicle in the database and accounts for only 1 catastrophic failure. Future researchers in this field must determine a way to predict subsystem reliability numbers for future 2nd and 3rd generation RLVs. It is expected that such estimates, by necessity, will rely on subsystem ground test results and analytical failure modes analyses. Unfortunately that data is not typically published in non-proprietary sources.

8. References

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Appendix I: Uses of Reliability Estimates

The reliability data generated previously can be used to project the reliability of the future launch vehicles for the conceptual vehicle design phase.

The following example demonstrates the engine set reliability calculation with single engine-out capability -- which means the launch vehicle envisioned in this analysis is capable of successfully achieving its objective with one engine failure during its operation. The reliability is calculated via binomial distribution and the equation derived for such system as following.[4]

$$R_{eo} = p^n + np^{(n-1)}(1-p) \qquad \text{(AP1)}$$

R_{eo} is the engine cluster reliability, p is the single engine reliability and n is the number of engines in a set with one engine out capability.

For this analysis, n is set to be 3 and p parametrically varied from 0.8 to 1.0. Table A1 and Figure A1 shows the engine set reliability of 3 engines with 1 engine out capability and comparison engine cluster of 2 engines with no engine out capability.

Table A1: Engine Reliability Analysis

Single Engine Reliability	Overall Cluster (Two engines/ No engine out)	Overall Cluster (Three Engines/One engine out)
0.8	0.64	0.96
0.82	0.6724	0.9676
0.84	0.7056	0.9744
0.86	0.7396	0.9804
0.88	0.7744	0.9856
0.9	0.81	0.99
0.92	0.8464	0.9936
0.94	0.8836	0.9964
0.96	0.9216	0.9984
0.98	0.9604	0.9996
0.9819	0.96412761	0.99967239
1	1	1

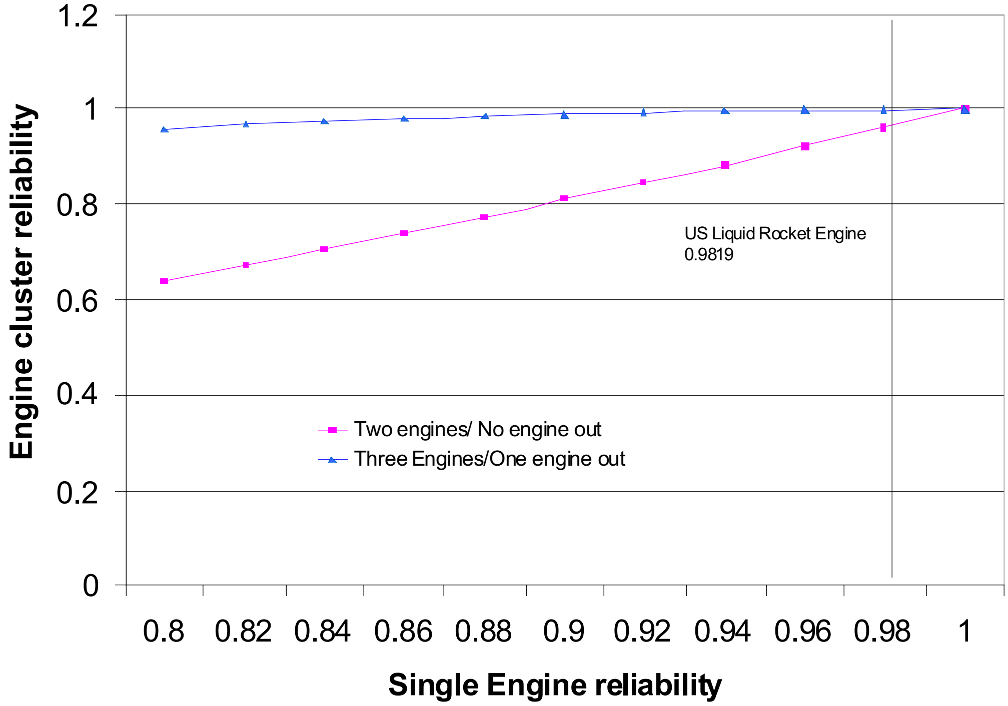

Figure A1: Engine Reliability Analysis

The data shows significantly better engine reliability for the engine cluster that allows for engine-out capability than the engine cluster that does not allow for engine out capability. But this gain in reliability diminishes as the reliability of the single engine improves.

With additional engine reliability data, this propulsion system analysis can be greatly expanded with following derived equation that accounts for the catastrophic failure fraction and converge time.[4,11]

$$R_{eo} = S^n T_d p^n \left(1 + T_u^{\,n-1} bn(p^{-c} - 1)\right) \qquad \text{(AP2)}$$

Parameters R_{eo}, p and n have same meaning as before, S is startup reliability (probability of engine failure at engine start), T_d is engine throttle down reliability, T_u is engine throttle up reliability, b is fraction of engine failures that don't lead to catastrophic failure and c is converge time and calculated by following equation.[4,11]

$$c = \frac{t_{MECO} - t_{eo}}{t_{MECO}} \tag{AP3}$$

The t_{MECO} is the Main Engine Cut Off (MECO) time and t_{eo} is the time when the single engine becomes inoperable.[11]

Appendix II: Complex General Aviation Aircraft System Definition[13]

Cockpit Instrument incorporates minimum instrumentation required for general aviation aircraft flying under Instrument Flight Rule (IFR) conditions defined in Federal Aviation Regulations (FAR) Part-91.

Electrical subsystem incorporates the lighting system and any components involved in source and distribution of electrical power.

Engine subsystem consists of any component or system that is essential to developing thrust for the aircraft.

Flight Control subsystem is composed of any component that controls the aircraft's attitude, heading and altitude or changes the aerodynamic characteristics of the aircraft in flight.

Ground Control subsystem includes any system of the aircraft that control the airplane's heading and speed on the ground. This subsystem classification does not include the power plant but includes retractable landing gear, hydraulic system and ground steering system.

Non-Engine Propulsion consists of any system that contributes to providing fuel through the engine-driven fuel pump, including fuel tanks, fuel lines, fuel cutoff switches, fuel filter, tank switches and fuel boost pump, and it is equivalent to Propellant Feed System of the launch vehicle.

Structure consists of any component or structure that is essential to the structural integrity of the aircraft. Even though they are not considered part of the structural integrity of the aircraft, the interior upholstery, the aircraft paint and static wicks are included in structure subsystem.