Analysis of Space Launch Vehicle Failures and Post-Mission Disposal Statistics

Lucía Ayala Fernández1 · Carsten Wiedemann1 · Vitali Braun2

Received: 21 February 2022 / Revised: 27 April 2022 / Accepted: 29 April 2022 / Published online: 21 May 2022
© The Author(s) 2022

Abstract
In a time in which a significant number of launch vehicles are being developed, boosted by numerous new space actors demanding cheaper access to space, the need to ensure the reliability of launch vehicles and the performance of a successful Post-Mission Disposal (PMD) is undeniable. The first step to ensure the reliability of new launch vehicles is to analyse previous launch failures, learning from past mistakes. In this paper, the launch failures that occurred over the past 16 years are analysed. These failures are classified as a function of the subsystems involved in the failure, as well as the phase of the mission in which the failure occurred. As a result, the most critical subsystems are identified for every mission phase. Subsequently, the most critical subsystem is further investigated, and its most critical components are identified. Furthermore, aiming to improve the present PMD practices, an understanding of the current status is necessary. This paper provides an overview of the evolution in terms of mean orbital lifetime of the rocket bodies launched since the year 2000. Moreover, the number of manoeuvres performed and the orbital lifetime saved by these manoeuvres is analysed between 2016 and 2020, further classifying the statistics by launcher family and country.

Keywords Launcher · Failure · Post-mission disposal · Reliability

1 Introduction
The commercialization of the space sector is already a reality that has been developing over the past few years. The paradigm shift known as NewSpace has changed the nature of the missions being launched, leading to smaller systems providing services from space with much smaller budgets than traditional space missions funded by states. This tendency has given rise to an exponential growth of actors in the space sector, resulting in a steep increase of the launch rate. These new space actors are demanding cheaper access to space, and numerous launch vehicles are being developed aiming to answer this demand. However, some concerns should be kept in mind while carrying out these developments, such as the sustainability of the space environment and the impact of the space sector on the Earth environment.

The increase in the launch rate has been significant. Only between 2016 and 2021 there was an increase of about 70% in the number of launch attempts per year. However, the success rate of the launchers in 2020 was the lowest one in this entire period. Launch failures come not only at a great economic cost but also at a large waste of resources. Even further, launchers which fail to perform a successful Post-Mission Disposal (PMD) can pose a risk either on ground, due to uncontrolled reentries of large stages; or on the space environment, when these stages remain orbiting for long time periods threatening other space missions and potentially contributing to the collisional cascading effect known as Kessler syndrome.

In this context, ensuring the reliability of launch vehicles becomes essential, as well as the performance of a successful PMD. Analysing previous launch failures provides relevant information to shape reliability efforts for the upcoming vehicles. Moreover, an analysis of the current PMD practices provides valuable information towards their improvement. This paper has therefore two focuses: Sect. 2 analyses the failures occurred between 2016 and 2021, including a classification by launch vehicle size, by subsystem originating the failure and by the mission phase in which the failure
occurred. Furthermore, once the subsystem introducing most failures is identified, the failures originated by this subsystem are studied in more detail. Section 3, on the other hand, analyses the PMD practices since the year 2000, focusing on the orbital lifetime of the rocket bodies as well as the manoeuvres performed to reduce this lifetime. The periods for the analyses were chosen simply depending on the availability of the data.

2 Launch Failures

2.1 Introduction

With the aim to improve the reliability of current launch vehicles, the first question that needs to be asked is: why do launchers fail?

This question can be divided into several parts:

1. What are the subsystems involved in the majority of launch vehicle failures?
2. For the most critical subsystem, what are the elements involved in the majority of the failures?
3. Which mission phases are the most critical? Or, during which mission phases do failures usually occur?
4. Which subsystems are the most critical for each mission phase?

Additionally, other questions can be useful to identify patterns in these failures:

5. Which type of launcher, thus which launcher size, fails the most?
6. Has this changed over time?
7. Does the most critical subsystem vary depending on the launcher size?
8. What is the proportion of launch failures that occurred during first version flights?
9. Has the number of first version flight failures changed during the past years?

This analysis includes the launch failures that occurred between the 1st of January 2006 and the 31st of December 2021. In order to conduct this analysis, every failure registered in the launch logs [1–3] was investigated and classified individually. To do so, the main sources of information were online news portals such as [4–7] and official communication by space agencies [8, 9] and companies [10–13]. The specific sources and classification for each launch failure were kept on an Excel spreadsheet and the statistics in the following sections were derived. A total of 79 failures were studied, while 5 additional unconfirmed failures were excluded from the analysis. However, due to the confidentiality that usually revolves around the development of launch vehicles, information about the causes of 22 of them was not found publicly available. It is also important to note that partial failures, thus launches in which the payload reached a different orbit than intended, were also considered failures for the intent of this study.

2.2 Failures Per Year, Launcher Size and Evolution with Time

To provide some context, the number of failures and success rate per year, as well as the launcher size is analysed. Figure 1 shows the number of launch attempts per year, divided by launch successes and launch failures, as well as the success rate, which is defined as the number of launch successes divided by the number of launch attempts in a year. It can be observed that the launch rate, thus the number of launches, has significantly increased in the last years. However, the success rate for these launches did not increase accordingly. Indeed, the launch success rate in 2020 was the lowest of the last 15 years, with the highest number of launch failures until then.

This high number of failures can be due to many factors. The undergoing development of a big number of new launcher systems is one possible influencing factor, due to the lower maturity of these launchers compared to the ones that are already flying for years. Figure 2 shows the number of failures per year and which of these failures occurred in a launch vehicle version that was flying for the first time, according to the data found in [3].

It can be observed that, indeed, the number of first version flight failures has increased in the last years and especially in 2020, when the highest number of first version failures is observed. However, there seems to be a comparable concentration of first version flight failures between 2006 and 2010. To understand better the data, these failures require a closer
look. During the period between 2006 and 2008, 3 out of 4 first flight failures correspond to the Falcon 1 launch vehicle. In this case, [3] considers the three Falcon 1 launches as a first version flight due to the fact that they were still versions in development, which implies significant changes in the launch vehicle between those flights. The other first version flight failures during the period between 2006 and 2010 come from either national agencies or governments which started developing their space access capabilities during these years, namely the Safir-1A vehicle from Iran and the KSLV-1 from South Korea, or from established companies and national agencies developing new versions of existing launch vehicles, as is the case for GSLV Mk.2(1), GSLV Mk.1(3), Proton-M Blok-DM-03 and Taurus-XL (as named in [3]).

The situation has, therefore, changed in the last years, where, in addition to the usual newly developed versions by established launch companies and national agencies, we can find several emerging companies developing their own launch vehicles. Some examples include Rocket Lab, which has been launching its Electron rocket to orbit since 2017, LandSpace which performed its first attempt in 2018, OneSpace in 2019, Virgin Galactic and Astra in 2020 or Firefly Aerospace with its first launch attempt in 2021. Most of these companies focus on the development of so-called microlaunchers, aiming to deploy small payloads in Low Earth Orbit (LEO). Therefore, a maybe more representative way to evaluate the impact of the NewSpace phenomena on the number of launch failures on the last few years is the classification of the failures according to the launcher size. The payload capacity to LEO needed to classify the launchers was obtained from [15] and from the respective launcher manuals.

Figure 3 shows the launch failures per year classified according to the size of the launcher. A steep increase in the number of failures caused by microlaunchers can be observed after 2018. This is probably due both to a shift in the market towards a higher use of microlaunchers and to the lower maturity of these systems, as well as a lower expertise from the new emerging companies that are developing these launchers. It can be observed that until 2016 the failures were dominated by medium size launchers, but in the last years the trend has clearly shifted.

### 2.3 Launch Failures by Subsystem

The first analysis performed involves the classification as a function of the subsystem that caused the failure. It is first important to note that launch failures are very complex and commonly more than one subsystem is involved. In order to apply a common criteria, the authors have attempted to always classify the failure according to the subsystem where
the first fault occurs, despite other subsystems contributing to the final failure. Moreover, the failures for which the cause is not publicly known are not shown in the graphs. Consequently, the data in Fig. 4 corresponds to a total of 57 failures. The subsystems considered are the following:

- Propulsion System (PROP).
- Trajectory and Attitude Control System (TACS).
- Power Storage and Distribution System (POW).
- Telemetry (TEL).
- On-Board Computer (OBC).
- Thermal Control System (TCS).
- Structures (STR).
- Separation Systems (SEP).

The resulting classification of the failures is shown in Fig. 4. It is first important to note that the majority of the failures were caused by the propulsion subsystem. This result is not surprising considering that this subsystem performs the most essential task of the launch vehicle, namely accelerating the launcher itself and the payload to orbital speed, in addition to being a very complex system working under extreme conditions. The failures of the propulsion system will be further studied in Sect. 2.5.

It is, however, interesting to look more closely at the failures related to the TACS and the SEP, being the next contributors to the failures. Indeed, these three subsystems together account for a 90% of the launch failures. First, it is important to highlight that the TACS can be divided into its software and hardware parts. This distinction was not made initially because it is not always easy to infer from the press announcements which one of them failed. However, in the cases in which more detailed information is provided, this distinction is useful to gain a better understanding of the TACS failures. From a total of 10 TACS failures recorded, 2 can be assigned to software errors and 4 to hardware errors, being the other 4 undefined. Both software errors occurred due to wrong initial settings for the launch [16, 17]. Some of the most surprising hardware errors occurred due to improper installation, such as the angular rate sensors installed upside down in a Proton rocket in 2013 [18] or the wrong routing of the control lanes of the AVUM upper stage that caused the inversion of the steering commands and the consequent loss of a Vega mission in 2020 [19].

Interestingly, despite being installation errors, these failures could also be prevented by design changes that do not allow for such mistakes. Another example was the close installation with an aluminum clamp of a hydrazine line and a super cold helium pressurization line in a Soyuz operated by Europe, which provoked the hydrazine to freeze and led to stoppage of the fuel supply for two attitude thrusters, eventually turning into two Galileo satellites injected into far from nominal orbits. Since nothing in the production manual advised against such installation, the inquiry board for the accident concluded that this was a “design deficiency” [20].

For the separation failures it is interesting to distinguish which separation failed. For the 10 recorded separation failures, 5 corresponded to a fairing separation failure. The cause is not specified for 3 of them [21–23], while for the 2 remaining ones (2 Taurus-XL) it was associated with improper extrusion material properties of a frangible joint [24]. On the other hand, 2 of the remaining failures correspond to payload separation [25, 26], 2 to stages separation [27, 28] and 1 to strap-on boosters separation [29]. The irregular strap-on booster separation is worth noting, as it corresponds to the only crewed launch vehicle that failed during the studied period. Deformed separation contact sensors in a Soyuz launcher provoked the abnormal separation of one of the four strap-on boosters of the launch vehicle, which impacted the core stage in the fuel tank area and caused a loss of attitude control. The mission was aborted and, fortunately, the crew capsule separated safely from the rocket, bringing the two-person crew on board safely back to Earth [29].

### 2.4 Launch Failures by Mission Phase

The same analysis as in Sect. 2.3 is performed here, additionally dividing the failures by mission phase. The typical phases of the mission profile of a reusable launch vehicle include:

- **Ascent:** starts at lift-off and it is considered to last until the separation of the last stage. It usually includes a vertical lift-off, pitch-over manoeuvre, and stages and fairing separation. It can also include coast phases.
- **Payload injection:** starting from the separation of the upper stage, it includes all the manoeuvres required to inject all the satellites in their intended orbits. It usually includes both propelled and coast phases.
• **Decommissioning**: from the injection of the last payload until the safe disposal of the upper stage, it will typically include a manoeuvre to lower the perigee and the passivation of all energy sources left on the stage. This phase can be superimposed to the payload injection phase, when the orbit of the secondary payloads is lower than this of the primary one.

• **Recovery of the reusable stages**: from the separation of the reusable stages to their landing, usually including flip manoeuvre, entry burn and aerodynamic guidance.

However, due to the difficulties to find information about failures during the PMD, failures occurred during this phase were not considered in this first analysis. Nonetheless, an analysis of PMD statistics will be carried out in Sect. 3. Moreover, due to the very limited amount of existing reusable launch vehicles, the failures during the recovery of reusable stages were also not analysed in this work. Therefore, the data reflected in this section only corresponds to failures occurred during the ascent and payload injection phases.

For this analysis, there were 11 failures that could not be classified by mission phase. The failures were almost evenly distributed among both phases, with 36 failures during the ascent and 32 during the payload injection. However, the subsystem causing the failure could not be determined for 3 ascent failures and 8 payload injection failures, providing a total of 33 failures classified by subsystem for the ascent phase and 24 for the payload injection phase. The resulting classification of the failures by subsystem for the ascent and payload phases is shown in Fig. 5.

In both phases, the propulsion system keeps accounting for the majority of the failures, with a 49% of the failures during the ascent and as much as a 63% during the payload injection phase. The TACS and the separation systems also remain as the next contributors, but with significant differences between both phases. For instance, most failures due to the separation systems occurred during the ascent phase, while the TACS accounts for a bigger share of the payload injection failures. This is coherent with the fact that more separations are required during the ascent, including the separations between stages and the fairing separation, while only the separation of the payload takes place during the payload injection phase. Moreover, all the failures caused by the TCS occurred during the ascent, which can be related to the higher thermal loads typical of this phase.

### 2.5 Launch Failures Due to the Propulsion System

As it has been shown, the propulsion system was involved in the majority of the launch failures studied. Therefore, a further analysis has been performed to better understand these failures. From the 31 failures corresponding to the propulsion system, only one corresponded to a solid rocket motor, while the other 30 corresponded to Liquid Rocket Engines (LREs). Therefore, the analysis below has been performed only for the failures corresponding to LREs. First, the LREs have been considered to be divided into the following components or subsystems:

- Tanks.
- Thrust chamber.
- Feeding system.
- Pipes and valves.
- Structures.
- Thurst Vector Control (TVC) system.

It is important to note that the pipes and valves could be considered as a part of the feeding system, and the TVC system as a part of the thrust chamber assembly. They have been separated only to obtain more specific information about the failures.

Figure 6 shows the result of the classification of the propulsion system failures (only including LREs) according to the subsystem that initiated the failure. As it occurred with the previous classifications, it is not always easy to determine which is the first subsystem provoking a failure. In cases in which there were doubts regarding the subsystem first originating the failure, the subsystem in which the corrective actions were performed has been chosen, as it is assumed that the corrective action applied in this subsystem should have prevented the failure.

It is first worth to mention that four of the failures could not be classified, remaining as unknown causes, and therefore the following graphs refer to the 26 failures that were classified. However, three of these unclassified failures provided some details, just not enough to be classified in this analysis.
It can be observed that as much as a 65% of the failures of the propulsion system were originated in the feeding system when the pipes and valves are considered as a part of this system. Indeed, more than a 30% of the propulsion failures were originated in the pipes and valves, which are a necessary part of any feeding system. From the 8 failures classified as pipes and valves, 4 involved a fuel leak, two of them being caused by the rupture of a fuel line [30, 31] and two by a valve failing to close [32, 33]. Another failure also involved the rupture of a pipeline, but in this case of the gas duct between the gas generator and the propellant pump [34]. Moreover, a debris object blocking a fuel intake caused two more failures [35, 36]. Finally, a small metallic orifice inside a fuel line originated a failure by preventing the engine from delivering sufficient thrust [37].

Regarding the failures assigned to the feeding system, four out of the nine failures were due to a debris infiltrated in the feeding system [38–41]. The other five failures were originated from the complex operating conditions of turbopumps. This included a damaged bearing [42], the ignition of a turbopump due to contact between rotating and stationary components [43], the degradation of turbopump material causing imbalance and high vibrations [44], the failure of a turbopump’s exhaust structure due to the complex thermal conditions [45] and the failure of a turbopump due to either gripping at seal and seizure of the rotor or rupture of the turbine casing due to pressure rise and thermal stresses [46].

The next contributor to the propulsion failures was the thrust chamber. However, only three failures were assigned to this subsystem, which makes its contribution much smaller than this of the feeding system and the pipes and valves. These failures involved a too high chamber pressure originated from a failed propellant regulator, which turned into one failed engine and eventually loss of control when the vehicle reached transonic regime [47]; a flaw in the material of the engine jacket, which ended up causing a breach and the consequent depressurization of the combustion chamber [48]; and an igniter failure due to unique environmental pressure and conditions [49].

One of the failures originated in the propellant tanks was related to the lack of slosh baffles in the tank design. The consequent sloshing of the liquid oxygen inside the tank caused control oscillations that grew in pitch, yaw and finally also in roll, which eventually centrifuged the propellants provoking a flame in the engine [50]. The second failure originated in the tanks was due to a pressure vessel filled with helium that became loose, accelerating upwards and hitting the top of the tank with great force. The reason why the vessel became loose was traced down to a bolt, which used a material that was not properly modeled or tested for the application. Additionally, material defect, manufacturing damage or improper installation might have contributed to the failure [51].

The failure attributed to structures originated with “the loss of structural integrity of a bolted interface that attaches the Stage III steering engine turbopump to the main engine structural frame” [51]. This led to an excessive vibration environment that damaged a fuel line, generating a fuel leak that resulted in the loss of stage control and mission. On the other hand, the failure originated by the TVC system was due to the malfunction of an oil pump that pressurizes the gimbal actuators of the first stage engine, which was not built to specifications [52].

Finally, the two failures listed under Other are the ones that could not be attributed to any of the previous subsystems. One of them was caused by overfueling of the Block DM-3 upper stage of a Proton launch vehicle, which forced the rocket to carry between 1 and 2 tons of extra weight resulting in a too low suborbital drop-off point [53]. The second failure involving the Astra Rocket launch vehicle was due to an inadequate oxidizer to fuel mixture ratio, which led to the rocket depleting all its fuel before reaching orbital speed.

3 Post Mission Disposal (PMD)

3.1 Introduction

In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) established the IADC Space Debris Mitigation Guidelines [54], a set of ground rules aiming to the preservation of the near-Earth space environment by mitigating the orbital debris produced by space missions. Even though these guidelines are not legally binding, codes of conduct of national space agencies and even national laws aiming to the protection of the space environment have been derived from these guidelines.
The term Post-Mission Disposal refers to all the actions a space vehicle needs to perform after its mission is completed to mitigate the risk it poses to other space vehicles [54]. In the guidelines, two protected regions are defined:

- The Low Earth Orbit (LEO) protected region, defined by a sphere at an altitude of 2000 km over the Earth surface.
- The Geostationary Orbit (GEO) protected region, which comprises a segment of a spherical shell which is limited in altitude by the altitude of a geostationary orbit plus and minus 200 km and in geocentric latitude by -15° and 15°.

The PMD actions to be performed depend on the orbital regime [54]. Space vehicles operating in LEO or orbits interfering with the LEO region must be cleared from the LEO protected region in less than 25 years, with a probability of success of at least a 90%. The options include a direct re-entry (preferred) or a manoeuvre to a lower orbit with a residual orbital lifetime of less than 25 years. In cases in which the operational orbit already has an orbital lifetime which is lower than 25 years, no actions are required in this respect. Moreover, when a space vehicle re-enters Earth’s atmosphere, the risk on the ground must be assessed, ensuring that it does not pose a risk on people or property. Additionally, if a direct re-entry is not performed, passivation of all on-board energy sources is required to minimize the risk for on-orbit break-ups. Space vehicles operating in GEO, on the other hand, must manoeuvr towards an orbit that is far enough from GEO to not to cause any interference with other space missions operating in this region for at least 100 years. Once the disposal orbit is acquired, passivation is also required.

Rocket orbital stages are a very particular type of space vehicles. Firstly, because their missions usually end almost as soon as they reach orbit, when they inject their payload or payloads into their desired orbits. Secondly, because they carry large propulsion systems. This propulsion system can be easily used to de-orbit the stage if enough propellant is available. However, if a de-orbit burn is not performed and the stage is not passivated, this propulsion system can also be source of on-orbit explosions. Indeed, a majority of orbital fragmentations have been historically related to propulsion causes [55]. Furthermore, rocket bodies have historically been large systems, which not only turns into a bigger risk of collisions but also means even more catastrophic consequences if a collision would happen. Therefore, limiting the time on orbit of rocket stages should be a priority.

This analysis will therefore focus on the orbital lifetime of the rocket stages and the manoeuvres performed to limit it. The existing database has been extracted from the Database Information System Characterising Objects in Space (DISCOS) database which is maintained by the European Space Agency (ESA) and from the TLE data available in Space-track [56]. This dataset contains all the rocket bodies that have been put in orbit since the 1st of January of 2000 until the 31st of December 2021, including their launch epoch, re-entry epoch if they already re-entered, and the data of the last orbit available. Moreover, for the rocket bodies launched between the years 2016 and 2020 (both included) data was provided by the Space Debris Office at ESA about whether they manoeuvred or not. This dataset will be used first to analyse the orbital lifetime of the objects operating in LEO or in orbits that intersect the LEO region. Then, the manoeuvres that were performed and their impact on the orbital lifetime are studied. Finally, the compliance with the 25 years guideline is assessed by the launcher family and by country associated to the launcher, as well as the manoeuvres executed to ensure this compliance.

### 3.2 Time on Orbit

To study the orbital lifetime of the rocket bodies in orbit the OSCAR (Orbital SpaceCraft Active Removal) tool from the DRAMA-3.0.4 (Debris Risk Assessment and Mitigation Analysis) software has been used. For a given orbital state and epoch, OSCAR propagates the orbital state until a re-entry is found to occur, returning a re-entry epoch as well as a final orbital state. For these propagations, the mass and average cross section data which are also available in DISCOS have been used. For the stages for which the average cross section was not available, the cross section has been calculated using the diameter and assuming a circular cross section. Finally, when these data were not available research has been made through specific websites, and when the required information was not found assumptions were made by comparison with similar stages. Furthermore, the latest orbital state and epoch available when the dataset was extracted were used for the propagations. In cases in which there was not orbital data available the registered destination orbit was used, with the launch date used as orbit epoch. Finally, only the rocket bodies intersecting with the LEO-protected region were considered in this analysis. The dataset comprises 1850 rocket bodies, 1478 of which have orbits intersecting with LEO.

Figure 7 shows the results of averaging the orbital lifetime of all the rocket bodies that were launched each year. Even if the values oscillate, the tendency is clearly decreasing. Especially surprising is the comparison between the worse year in the dataset, namely 2002, with 34.97 years of average lifetime, to the best one, corresponding to 2020, with 5.35 years of average orbital lifetime. Moreover, since 2014 the average lifetime has been below the 25 years threshold for all years. However, considering that all objects should comply with the 25 years guideline, a much lower orbital lifetime
should be aimed for. It must also be noted that for the sake of computational time, OSCAR was run for a maximum of 100 years of propagation, which means that the orbital lifetime of all objects remaining on orbit for longer than 100 years was considered only as 100 years. Thus, the average orbital lifetime represented here is expected to be a bit lower than the actual average lifetime.

Figure 8 shows the distribution of the objects in different intervals of the orbital lifetime depending on their year of launch. It can be observed that a big proportion of the objects re-enter within a year from their launch date, which is very good news. Indeed, a 74.3% of the objects included in the study was compliant with the 25 years rule, with this number going up to an 86.8% for objects launched in the last 5 years. However, there is still a big part of objects taking more than 50 years to re-enter, posing a risk on future space missions and in the sustainability of the space environment. Luckily, this proportion of long orbiting objects which was as high as a 32.7% in 2002 has also been reduced, going down to a 3.2% in 2020 but unfortunately back up to a 10.0% in 2021.

### 3.3 Manoeuvres

The dataset including information about whether the stage performed a PMD manoeuvre or not includes the rocket bodies launched between the 1st of January 2016 and the 31st of December 2020. This dataset includes a total of 449 objects, out of which 198 performed a PMD manoeuvre. Figure 9 represents the orbital lifetime of all the rocket bodies in the data set which did perform a PMD manoeuvre, represented by their launch date. For this part of the analysis, the OSCAR simulations were run for a maximum of 300 years. Thus, the red dots represented in the figure as 300 years lifetime would most likely remain in orbit for even longer.

As it could have been expected, most of the objects that manoeuvred complied with the 25 years guideline. More specifically, 178 out of the 198 rocket bodies which performed a PMD manoeuvre between 2016 and 2020 have resulting orbital lifetimes below 25 years. However, it is still surprising that 20 of these objects had orbital lifetimes above 25 years despite the manoeuvre, including even 6 objects with orbital lifetimes above 300 years after the manoeuvre. Indeed, 13 of these 20 objects had orbital lifetimes above 50 years even after the manoeuvre. We can take a closer look at the 6 rocket bodies with orbital lifetimes above 300 years despite the manoeuvre, which could be the most surprising ones. One of them, corresponding to a H-IIA launcher, was launched into Geostationary Transfer Orbit (GTO) and the PMD manoeuvre was performed to lower the apogee so that the orbit would not intersect with GEO. However, there was
apparently no intention to clear out faster from the LEO region, as the resulting perigee was even higher than the initial one, resulting in a longer remaining orbital lifetime after the manoeuvre. Another of these rocket bodies, corresponding to a Rokot launcher, performed the manoeuvre to a slightly higher orbit. It is therefore probable that the intention of this manoeuvre was only to clear out from the operational orbit of the payload, rather than complying with the space debris mitigation guidelines. The last four objects, corresponding to two Rokot and two Long March (2D and 11 respectively), performed a manoeuvre to lower the perigee, but still left the stages in orbits very far from being compliant with the 25 years rule. It can be assumed that either the manoeuvre failed, or the only intention of the manoeuvre was to clear the payload’s operational orbit.

It can also be mentioned that there were cases in which manoeuvres raising the perigee of the orbit were performed to remove the rocket body from the LEO protected region. These are not included in the analysis, as their orbits are not intersecting with LEO any more. However, it can also be noted that this disposal option is not included in the IADC guidelines [54], as these objects are likely to end up interfering with LEO again in the future.

Now the remaining orbital lifetime of the rocket bodies which manoeuvred can be compared with the orbital lifetime that they would have had if the manoeuvre would not have been performed. To do this, the destination orbits were propagated using the launch date as orbit epoch. Figure 10 shows the resulting orbital lifetime that was saved by each manoeuvre as function of its launch date, and separated by colors in controlled and un-controlled re-entries. It must be noted that for the manoeuvres that raised the orbit instead of lowering it, the lifetime saved was considered as 0, as they did not intend to reduce the orbital lifetime.

There is a high number of manoeuvres which saved even less than one year of orbital lifetime. These manoeuvres typically correspond to objects which were already in low orbits and would have re-entered in a very short time, but a controlled re-entry was performed anyway. This was probably done to comply with the requirement to not to pose a risk to people or property on ground, as the stages performing this controlled re-entries are typically large stages which would not completely disintegrate in the atmosphere, implying that a controlled re-entry over an unpopulated region is required to mitigate the risk. Another proportion of manoeuvres which did not provide a significant reduction of the lifetime comes from the objects which did not reduce the orbit enough to re-enter, but only cleared the operational orbits of their payloads.

On the other hand, some manoeuvres introduced a significant reduction in the orbital lifetime of the stages, up to even 300 years. Indeed, the lifetime reductions of 300 years imply that the propagation duration limit was reached by OSCAR, so the actual lifetime of these stages would have been even larger. To obtain this 300 years orbital lifetime reduction, these stages performed a direct re-entry. This sets a very positive example of the behaviour that is needed to maintain the sustainability of the space environment.

In total, 8848.65 years of the orbital lifetime were reduced by 198 manoeuvres, providing an average of 44.69 years of orbital lifetime reduction per manoeuvre. However, this average is highly influenced by outliers, thus by the objects achieving a 300 years reduction of the orbital lifetime. As a result, this average can be misleading. To reduce the influence of outliers, the median was also computed, resulting in 4.29 years of median lifetime reduction, which is one order of magnitude lower than the average.

### 3.4 PMD by Launcher Family and Country

To gain a better understanding of current PMD practices, the differences between launcher families and between countries have been examined. Figure 11 shows the number of rocket bodies that were put on orbits crossing the LEO protected region between 2016 and 2020 by launcher family. The green and red bars differentiate whether the stage manoeuvred or not. The average orbital lifetime of the rocket bodies of each launcher family is represented by a blue line, while the dashed purple line represents the average orbital lifetime of these rocket bodies in case they would not have manoeuvred. The launcher families that performed less than 5 launches during the 5 years considered were discarded from all the plots.

It can be seen that some launcher families did not perform any manoeuvres, such as Ariane 5, SLV-P or Antares.
200, and some only did very rarely, like Electron with only 1 manoeuvre out of 28 rocket bodies on orbit. In these cases, the average orbital lifetime and the average orbital lifetime without manoeuvres overlap, as it could have been expected. More surprising might be the case of launcher families such as Atlas V or Polar SLV, for which the average lifetime with and without manoeuvre overlap despite a significant proportion of manoeuvres performed. In the case of the Polar SLV, some manoeuvres appear to have the only intent to remove the stage from the operational orbit of the payload, as some of them are even moved towards slightly higher orbits. On the other hand, the apparent overlap of the lifetimes in the Atlas V family is due to the performance of controlled re-entries in stages that were already in very low orbits, presumably aiming to reduce the risk on ground. This practice can also be observed in other launcher families such as Falcon. Moreover, some of the Atlas launches that performed a direct re-entry after completing their mission were military missions, which means that a destination orbit was not provided and the lifetime without manoeuvre could not be computed. Some of the families with lower average orbital lifetimes are Antares 200, Soyuz-2, SLV-P, Atlas V and Kuaizhou, in order from lower to higher, all of them with an average orbital lifetime below 2.5 years. However, the only one from this launcher families which achieved a significant reduction of the orbital lifetime by the manoeuvres was the Soyuz-2, meaning that the other four are simply launching directly to very low orbits with reduced orbital lifetimes. Vega and Electron also achieved significantly low orbital lifetimes, with 5.9 and 6.7 years respectively. While Vega achieved this low orbital lifetime by performing PMD manoeuvres, which reduced its average orbital lifetime by 88.2 years, Electron did so by mainly performing launches to significantly low orbits.

It is also easy to observe that the highest peak in orbital lifetime corresponds to the Rokot launcher family. Even though most of these launchers performed a PMD manoeuvre, reducing the average orbital lifetime of the family by as much as 116.26 years, these manoeuvres were far from being enough, resulting in an average orbital lifetime of 183.74 years. Furthermore, the 300 years propagation duration limit was reached by 4 of the 7 Rokot rocket bodies considered, meaning the average lifetime is even underestimated with respect to reality. Additionally, the number of families which did not achieve an average orbital lifetime below 25 years is significant. Namely H-II, Delta IV, Polar SLV, Ariane 5, Soyuz, Long March 4 and Long March 2, in order from higher to lower orbital lifetime. Finally, the highest reduction in the average orbital lifetime accomplished by PMD manoeuvres was achieved by Delta IV with 128.79 years, followed by Rokot and Vega.

Figure 12 shows the distribution of the rocket bodies in different intervals of orbital lifetime for each launcher family. It is clearly seen that the Rokot family has the highest percentage of long-lived objects, with only a 14.3% of the orbital stages re-entering within 25 years, which corresponds to only one of the launches occurred during the studied period. But even more worrisome is the fact that a 57.1% of the rocket bodies from the Rokot family have an orbital lifetime higher than 50 years. The Ariane 5 family did also not perform well, in comparison with other launcher families. Only a 4.3% of Ariane 5 rocket bodies re-enter within 10 years, but the percentage goes up to a 52.2% for re-entries within 25 years, and thus compliant with the space debris mitigation guidelines. However, this
is still a quite small percentage considering that all objects should be compliant with the guideline. In addition, Ariane 5 is the family with the second-highest percentage of objects above 50 years of lifetime, with a 30.4%. It can be noted that both Rokot and Ariane 5 started launching in the 1990s, before the IADC space debris mitigation guidelines were established and, therefore, were not designed to be compliant with them.

All other rocket families have a percentage of compliant objects above a 70%. Some positive examples can be highlighted, such as the Antares 200 family for which all objects are re-entering within 1 year, the SLV-P with all orbital lifetimes below 5 years, and Soyuz-2 and Kuaizhou always below 10 years.

Finally, the same analysis was also performed by the country associated with the launch vehicle. Due to the collaborative nature of the space industry inside Europe, it was treated as a country for this analysis. The countries which performed less than 5 launches during the considered time period (2016–2020) were excluded from the analysis.

Figure 13 shows the number of rocket bodies that were put on orbits crossing LEO by each country during the period 2016 to 2020. The green bars represent the ones that performed a PMD manoeuvre, while the red ones represent those which did not. The blue line represents the average orbital lifetime of these objects, and the dashed purple one represents the average orbital lifetime that these objects would have had if they none of them had perform a PMD manoeuvre. The country which performed more launches during this period was China with 131 rocket bodies on LEO crossing orbits, followed by the United States of America (USA) with 116. Both countries performed a PMD manoeuvre in more than half of these rocket bodies, more specifically in a 56.5% and a 58.9% respectively. These manoeuvres reduced the average lifetime in 17.1 years for the Chinese rocket bodies, and in 22.1 years for the American ones, resulting in average lifetimes of 18.1 years and 9.7 years respectively.

The lowest average lifetime is this of New Zealand, whose only contribution is from the Electron launcher, with 6.7 years. Sadly, Russia, Japan, Europe and India all have average lifetimes above the 25 years threshold, being Japan and Russia the highest with 44 and 40 years respectively. These

---

**Figure 12** Proportion of rocket bodies from a specific family falling within a specific lifetime interval

**Figure 13** The bars represent the number of rocket bodies put on orbits crossing LEO between 2016 and 2020 by country, separated by whether they performed a de-orbit manoeuvre or not. The lines represent the average lifetime of these rocket bodies and the predicted average lifetime if the manoeuvres would not have been performed.
high average lifetimes are highly influenced by outliers, thus by the rocket bodies staying in orbit for up to 300 years. More specifically in Russia’s case, this contribution comes from the Rokot launcher family. Europe and India both have average lifetimes close to the 25 years limit, namely 26 and 27 years respectively, but clearly more efforts are required to ensure the compliance of all launchers. Europe’s average lifetime is very influenced by the Ariane 5 launcher, which was not designed to perform a PMD manoeuvre and usually flies to GTO orbits, which have a significantly high orbital lifetime. Finally, the highest reduction of the average orbital lifetime was achieved by Russia with 33 years. However, this was clearly not enough given the high remaining orbital lifetime. Countries like Japan, India and New Zealand almost did not reduce their orbital lifetime with the corresponding PMD manoeuvres.

Figure 14 shows the distribution of the rocket bodies in different intervals of orbital lifetime for each country. Europe shows the least effective PMD practices of its launch vehicles, with only a 62.5% of rocket bodies compliant with the 25 years guideline while this percentage is above 80% for all other countries. Furthermore, only a 28.1% of the rocket bodies launched by Europe are re-entering within 10 years, while for all other countries this percentage is above a 55%. Finally, the percentage of objects with lifetimes above 50 years is also the highest for Europe, with a 21.9%.

4 Conclusions

With the aim to reduce the impact of space launch vehicles in the sustainability of both Earth and space environment, two different analysis have been performed.

The first analysis, which examined the launch failures occurred between 2006 and 2021, aims to help shaping future reliability efforts. To do so, the most critical subsystems of launch vehicles have been identified, namely the propulsion system, separation systems and trajectory and attitude control system. These three subsystems alone account for a 90% of launch failures, with a 54% corresponding to the propulsion system. These failures were then divided by mission phase. With the propulsion system dominating the failures in both the ascent and payload injection phases, the separation systems accounted for a bigger proportion of the failures than the trajectory and attitude control system during the ascent, while the opposite happened during the payload injection phase. These results are coherent with the nature of both phases. Finally, the failures originated from the propulsion system were studied in more detail, and the results signaled the feeding system as the main responsible for those failures.

It can be noted that a further classification of the failures according to their source would be useful to better understand the nature of the failures and identify possible mitigation strategies. For instance, if the failure occurred due to a design defect, human error or a manufacturing or assembly error, the correction actions to be taken will be very different. However, this information was only found publicly available for a small percentage of the failures. The scarce information found was not considered representative for the analysis carried out in this publication.

Secondly, the PMD practices of rocket bodies were examined closely. First, a general analysis focused on the orbital lifetime of rocket bodies interfering with the LEO region was performed for the time period between 2000 and 2021. Subsequently, the manoeuvre statistics were investigated in terms of the lifetime reduction achieved. These statistics were then divided by launcher family and by country, assessing the compliance with the space debris mitigation guidelines by each launcher family and by country as well as the efforts carried out to comply with these guidelines. It was found that the Rokot launcher family shows the highest average orbital lifetime, very far from the rest, despite performing a PMD in the majority of its launches. Moreover, all H-II, Delta IV, Polar SLV, Ariane 5, Soyuz, Long March 4 and Long March 2 show an average orbital lifetime above the 25 years threshold. The Rokot launcher family also shows the highest percentage of long-lived objects in LEO, followed by Ariane 5. From the point of view of the countries, only China, USA and New Zealand achieved an average orbital lifetime below the 25 years guideline, while the highest values were those of Japan and Russia. However, Europe shows the lowest percentage of rocket bodies compliant with the 25 years guideline, as well as the highest percentage of objects with orbital lifetimes above 50 years.
Acknowledgements  The project leading to this application has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie grant agreement No 860956.

Funding  Open Access funding enabled and organized by Projekt DEAL.

Declarations

Conflict of interest  On behalf of all authors, the corresponding author states that there is no conflict of interest.

Open Access  This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

References

1. Space Launch Report. https://www.spacelaunchreport.com/index.html. Accessed 27 Jan 2022
2. Spaceflight Now - Launch Log. https://spaceflightnow.com/launch-log/. Accessed 27 Jan 2022
3. Gunter’s Space Page - Chronology of Space Launches. https://space.skyrocket.de/directories/chronology.htm. Accessed 27 Jan 2022
4. Space.com. https://www.space.com/. 27 Jan 2022
5. Spaceflight Now. https://spaceflightnow.com/. Accessed 27 Jan 2022
6. NASA SpaceFlight. https://www.nasaspaceflight.com/. Accessed 27 Jan 2022
7. SpaceNews. https://spaceflightnow.com/. Accessed 27 Jan 2022
8. Roscosmos News. http://en.roscosmos.ru/102/201107/. Accessed 02 Dec 2021
9. ISRO Press Releases. https://www.isro.gov.in/press-releases. Accessed 02 Dec 2021
10. Astra Newsroom. https://astra.com/newsroom/. Accessed 02 Dec 2021
11. Arianespace Launch Log. https://www.arianespace.com/launch-log/. Accessed 02 Dec 2021
12. Rocketlab News. https://www.rocketlabusa.com/about-us/updates/. Accessed 02 Dec 2021
13. ILS Launch Services. https://www.ilslaunch.com/. Accessed 02 Dec 2021
14. McConnaughey, P.K., Femminineo, M.G., Koellgen, S.J., Lepsch, R.A., Ryan, R.M., Taylor, S.A.: NASA’s launch propulsion systems technology roadmap. Technical report, NASA (2010)
15. Gunter’s Space Page—Launch Vehicles. https://space.skyrocket.de/directories/launcher.htm. Accessed 27 Jan 2022
16. Soyuz Fails to Deliver 19 Satellites from Vostochny. http://www.russianspaceweb.com/meteor-m2-1.html#culprit. Accessed 02 Dec 2021
17. Independent enquiry commission announces conclusions concerning the launcher trajectory deviation during flight VA241. https://www.arianespace.com/press-release/independent-enquiry-commission-announces-conclusions-concerning-the-launcher-trajectory-deviation-during-flight-va241/. Accessed 02 Dec 2021
18. Roscosmos fingers botched sensor installation in July 2 proton failure. https://spacenews.com/36336roscosmos-fingers-botched-sensor-installation-in-july-2-proton-failure/. Accessed 02 Dec 2021
19. Loss of Vega Flight VV17: Independent Enquiry Commission Announces Conclusions. https://www.arianespace.com/press-release/loss-of-vega-flight-vv17-independent-enquiry-commission-announces-conclusions/. Accessed 02 Dec 2021
20. Soyuz Team Takes Steps To Prevent Repeat of Galileo Launch Failure, Including the Premature Celebration. https://spacenews.com/42119soyuz-team-takes-steps-to-prevent-repeat-of-galileo-launch-failure/. Accessed 02 Dec 2021
21. South Korean Rocket Will Launch Again in June. https://www.space.com/8129-south-korean-rocket-launch-june.html. Accessed 02 Dec 2021
22. Indian Navigation Satellite Stranded on Rocket After Launch. https://spaceflightnow.com/2017/08/31/pslv-c39/. Accessed 02 Dec 2021
23. Mystery Surrounds Chinese Private Rocket Launch Attempt. https://spacenews.com/mystery-surrounds-chinese-private-rocket-launch-attempt/. Accessed 02 Dec 2021
24. NASA Investigative Summary: Taurus XL T8 and T9 Mission Failures. https://www.nasa.gov/sites/default/files/atoms/files/oco_glory_public_summary_update___for_the_web___04302019.pdf. Accessed 02 Dec 2021
25. Roscosmos: Cause of Progress M-27M’s Emergency Establishment. http://en.roscosmos.ru/20473/. Accessed 02 Dec 2021
26. Russian Military Satellites Orbed by Stripped-down Soyuz Rocket. https://spaceflightnow.com/2015/12/06/russian-military-satellites-orbed-by-stripped-down-soyuz-rocket/. Accessed 02 Dec 2021
27. Russian Commission Completes Investigation. https://www.ilslaunch.com/russian-commission-completes-investigation/. Accessed 02 Dec 2021
28. Falcon1, Flight 3: Mission Summary. https://web.archive.org/web/20180927204157/https://www.spacex.com/news/2013/02/11/falcon-1-flight-3-mission-summary. Accessed 02 Dec 2021
29. Russia’s ID Cause of Soyuz Launch Abort, Release Dramatic Rocket Video. https://www.spaceflightnow.com/42319-soyuz-launch-abort-russia-identifies-cause.html. Accessed 02 Dec 2021
30. Falcon 1 Failure Traced to a Busted Nut. https://www.space.com/2643-falcon-1-failure-traced-busted-nut.html. Accessed 13 Dec 2021
31. Virgin Orbit Traces Cause of LauncherOne Engine Failure to Propellant Line. https://spaceflightnow.com/2020/07/25/virgin-orbit-traces-cause-of-launcherone-test-flight-mishap-to-propellant-line/. Accessed 13 Dec 2021
32. Mission Status Center—Thursday, August 16, 2007. https://web.archive.org/web/20071023173510/https://spaceflightnow.com/atlusav009/status.html. Accessed 13 Dec 2021
33. Launch and Learn: LV0006. https://astra.com/news/launch-and-learn-lv0006/. Accessed 13 Dec 2021
34. Russian Commission Determines Cause of AMC-14 Breeze-M Failure. https://www.ilslaunch.com/russian-commission-determines-cause-of-amc-14-breeze-m-failure/. Accessed 13 Dec 2021
35. China Great Wall Pins December Long March Launch Failure on Fuel-line Clog. https://spacenews.com/39687china-great-wall-pins-december-long-march-launch-failure-on-fuel-line/. Accessed 13 Dec 2021
36. Press Releases—On the Results of the Work of the Interdepartmental Commission (09/08/2011). http://www.khrunichev.ru/main.php?id=1&nid=2162. Accessed 13 Dec 2021
37. Proton Set To Return to Flight Oct. 14 Carrying Intelsat’s IS-23. https://spacenews.com/proton-set-return-flight-oct-14-carrying-intelsats-23/. Accessed 13 Dec 2021
38. Russian State Commission Issues Results of Proton Review. https://www.ilslaunch.com/russian-state-commission-issues-results-of-proton-review/. Accessed 13 Dec 2021
39. Sea Launch’s Odyssey Heading to Vancouver—Failure Update. https://www.nasaspaceflight.com/2007/05/sea-launchs-odyssey-heading-to-vancouver-failure-update/. Accessed 13 Dec 2021
40. Burn-through Blamed in China Long March Mishap. https://spacenews.com/burn-through-blamed-china-long-march-mishap/. Accessed 13 Dec 2021
41. Roscosmos News—Roscosmos. The Possible Cause of the Progress MS-04 Contingency (11/01/2017). http://en.roscosmos.ru/20665/. Accessed 13 Dec 2021
42. Turbopump Bearing Cited in Proton Upper-stage Failure. https://spacenews.com/turbopump-bearing-cited-in-proton-upper-stage-failure/. Accessed 13 Dec 2021
43. NASA and Orbital Reach Differing Conclusions on Antares Failure. https://spacenews.com/nasa-orbital-differ-on-root-cause-of-antares-launch-failure/. Accessed 13 Dec 2021
44. Russian statement on proton failure leaves questions. https://spacenews.com/russian-statement-on-proton-failure-leaves-questions/. Accessed 13 Dec 2021
45. China Reveals Cause of Long March 5 Failure; Lunar Sample Mission to Follow Return-to-flight. https://spacenews.com/china-reveals-cause-of-long-march-5-failure-lunar-sample-mission-to-follow-return-to-flight/. Accessed 13 Dec 2021
46. GSLV-D3 Failure Analysis Report. https://www.isro.gov.in/update/09-jul-2010/gslv-d3-failure-analysis-report. Accessed 13 Dec 2021
47. GSLV-F02 Failure Analysis Committee Report. https://www.isro.gov.in/update/06-sep-2006/gslv-f02-failure-analysis-committee-report. Accessed 13 Dec 2021
48. SpaceX Poised for 2nd Cargo Run to Station. https://spacenews.com/spacex-poised-for-2nd-cargo-run-to-station/. Accessed 13 Dec 2021
49. Rocket Lab Completes Anomaly Review, Next Mission on the Pad in July. https://www.rocketlabusa.com/updates/rocket-lab-anomaly-review-next-mission-on-the-pad-in-july/. Accessed 13 Dec 2021
50. SpaceX Demo Flight 2—Flight Review Update. https://web.archive.org/web/20081203154733/http://www.spacex.com/F1-DemoFlight2-Flight-Review.pdf. Accessed 13 Dec 2021
51. NASA Investigation Linked 2015 Falcon 9 Failure to Design Error. https://spacenews.com/nasa-investigation-linked-2015-falcon-9-failure-to-design-error/. Accessed 13 Dec 2021
52. Sea Launch Pinpoints Failure Cause, Aims to Return to Flight by Year’s End. https://spacenews.com/35138sea-launch-pinpoints-failure-cause-aims-to-return-to-flight-by-years-end/. Accessed 13 Dec 2021
53. Two Russian Space Officials Axed After Proton Failure. https://spacenews.com/two-russian-space-officials-axed-after-proton-failure/. Accessed 13 Dec 2021
54. IADC space debris mitigation guidelines. Technical report, Inter-Agency Space Debris Coordination Committee (March 2020)
55. Braun, V., Lemmens, S., Reihs, B., Krag, H., Horstmann, A.: Analysis of breakup events
56. Space-track. https://www.space-track.org/. Accessed 27 Jan 2022

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.