

A Systematic Comparison of Reusable First Stage Return Options

Sven Stappert, Jascha Wilken*, Leonid Bussler*, Martin Sippel**

**German Aerospace Center (DLR), Institute of Space Systems, Robert-Hooke-Straße 7, 28359 Bremen*

¹sven.stappert@dlr.de, jascha.wilken@dlr.de, leonid.bussler@dlr.de, martin.sippel@dlr.de

Abstract

The recent success of the emerging private space companies SpaceX and Blue Origin in landing, recovering and relaunching first stages have demonstrated the possibility of building reliable reusable launchers with low launch costs. Due to this risen interest in reusability, the project AKIRA was initiated by the German Aerospace Center (DLR) in 2017. This multidisciplinary project focuses on identifying and investigating key technologies for possible future reusable launch vehicles. Within this paper the focus is set on the comparison of different return options including vertical takeoff, vertical landing and vertical takeoff, horizontal landing on a technological and economic level.

Abbreviations

AoA	Angle of Attack
ASDS	Autonomous Spaceport Droneship
DRL	Downrange Landing
EC	Economical Condition
ELV	Expendable Launch Vehicle
FB	Flyback
GLOM	Gross Lift-Off Mass
IAC	In-Air Capturing
Isp	Specific Impulse
LFBB	Liquid Fly-Back Booster
LZ-1	Landing Zone 1
MECO	Main Engine Cut-Off
RLV	Reusable Launch Vehicle
RoRo	Roll On, Roll Off (Ship)
RTLS	Return to Launch Site
STS	Space Transportation System
TOSCA	Trajectory Optimization and Simulation of Conventional and Advanced Spacecraft
TRL	Technology Readiness Level
VTHL	Vertical Takeoff, Horizontal Landing
VTVL	Vertical Takeoff, Vertical Landing

1. Introduction

While reusability in space transportation can have a strong impact on the costs and thus competitiveness of space launchers, the historic Space Shuttle has also shown that this impact does not necessarily have to be positive if the refurbishment costs cannot be kept low. Nonetheless, the recent successes of SpaceX (with Falcon 9 and Falcon Heavy) and Blue Origin (New Shepard) in landing, recovering and reusing their respective booster stages by means of retropropulsion have shown the possibility of developing, producing and operating reusable launchers at low

launch service costs. This has raised the interest in introducing reusability to European launchers as a way to lower the launch costs and stay competitive on the evolving launch market. Reusability for launch systems can be achieved through a broad range of different technologies and approaches. Understanding and evaluating the impact of the different possible return and reuse methods on a technological, operational and economic level is of essential importance for choosing a technology that is adaptable to a European launch system.



Figure 1: SpaceX Falcon Heavy side booster using the VTVL method (left; photo by [SpaceX](#); CC0 1.0) and the LFBB representing the VTHL method (right) [1]

In order to assess the technological demands of reusable launch vehicles, the DLR project AKIRA was initiated in 2017 [2], [3]. Within this project the focus is set on understanding and raising the TRL of necessary technologies for RLVs such as cryoinsulation and thermal protection systems. Furthermore, the broad comparison of different return options to identify benefits and drawbacks of different return approaches is part of AKIRA.

In this paper two major approaches to reusability are considered and compared: vertical take-off and vertical landing (VTVL) and vertical take-off, horizontal landing (VTHL). The former approach is currently used by SpaceX to land the first stages of the Falcon 9 launch vehicle (see Figure 1) [4]. This method features the re-ignition of the first stage engines after MECO to perform several course correcting maneuvers. Finally, the stage lands vertically by means of retropropulsion. Additional flight hardware allowing for the required maneuvers and landing capability are aerodynamic control surfaces (e.g. grid fins for the Falcon 9) and landing legs. A certain amount of propellant is required to reignite and operate the engines and perform the required maneuvers.

The VTVL methods can be further divided into two different return possibilities: return to launch site (RTLS) and downrange landing (DRL). The first return strategy requires more propellant since the horizontal velocity has to be reverted and the stage brought back to its launch site. The second strategy requires a landing pad installed at the designated landing point downrange. Depending on the launch site and launch azimuth this might be a landing pad installed on land or a sea-going platform (e.g. landing barges for SpaceX, see Figure 2).

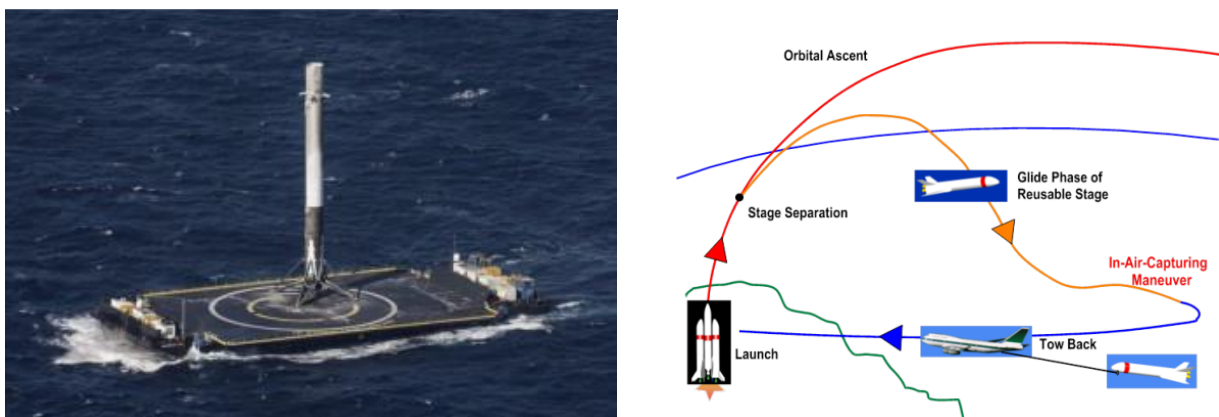


Figure 2: SpaceX Falcon 9 landed stage on a ASDS (left, Photo by [SpaceX](#); CC0 1.0) and sketch of an In-Air-Capturing mission (right)

The other method this paper is focused on is the VTHL approach. This method was first used with the STS or Space Shuttle. Furthermore, in the past several studies using the VTHL approach were carried out among which the Baikal concept [5], the Phoenix concept and its demonstrator HOPPER [6], the Liquid Fly-Back Booster study of the DLR [1] and the SpaceLiner concept of DLR [7] are worth mentioning. Contrary to the VTVL method, the deceleration of the stage following MECO is achieved by aerodynamic means without the use of the engines' thrust. Hence, the

respective stages feature wings and aerodynamic control surfaces to generate sufficient lift and drag for the required re-entry maneuvers. At the end of the mission the RLV stage lands horizontally on a runway or landing strip. Within the VTHL method further classification can be undertaken considering the return mode. One possibility is the so-called In-Air-Capturing. This concept is based on the idea to “catch” the returning stage downrange by a towing aircraft (see Figure 2) to tow it back to the launch site. This idea was studied in detail at DLR and is further demonstrated using sub-scale models within AKIRA and EU project FALCon, which the DLR leads. The second possibility is to return the stage by the use of turbine engines to the launch site. This idea, called flyback, requires the stage to be equipped with turbine engines as well as additional propellant and propellant supply systems.

The goal within AKIRA is to allow a comparison of the aforementioned return technologies. As the topic of reusability of launch vehicles is of high complexity different levels are considered in AKIRA. First, the technological differences and the impacts on system level are evaluated. Thus, the RLV methods are compared with respect to their impact on the launcher design on a system level. Additionally, the re-entry trajectories are compared regarding re-entry conditions and loads. Since this aspect was discussed in previous papers of DLR in detail ([8]- [10]) it will be just briefly touched in this paper.

A very important and highly controversial question is the economic and operational profitability and viability of RLVs. Hence, another important aspect of comparing RLV methods lies in the estimation of the RLV’s economics. However, the economics are difficult to assess especially considering refurbishment and maintenance costs. It is considered a fact that demonstrators are necessary to determine the impacts of different re-entry approaches on structures, TPS and the whole system. Currently, two different demonstrators are under development at DLR: CALLISTO, representing a VTVL launcher [11], and ReFEx, incorporating the VTHL approach [5].

Nevertheless, within AKIRA a comparison on operational and economic level is performed with the current knowledge available. Hence, this paper features a comparison of operational costs of the different return methods. For this recovery cost model a bottom-up approach was used which estimates the costs linked to RLV operations and recovery by using established cost models on subsystem level. The results of this operation and recovery cost model are presented and discussed herein.

It is important to note that further RLV methods, such as partial recovery of first stage elements or foldable wings for winged stages, are considered within AKIRA. However, these possibilities are not presented in this paper, since the current focus worldwide lies on VTVL and VTHL concepts and the status of projects such as ADELINe or the ULA SMART technology is unclear.

2. Methods and Assumptions

The above mentioned return options can be compared best if equal mission and design requirements are posed upon the conceptual designs. Generic assumptions and design processes were used to allow for maximum comparability of the shown vehicles. Hence, all configurations considered within this paper use the same key mission requirements:

- 7000 kg + 500 kg margin, payload to GTO of 250 km x 35786 km x 6° (standard Ariane 5 GTO) via a LEO parking orbit of 140 km x 330 km x 6°
- Launch from CSG, Kourou
- TSTO: Two Stage to Orbit
- Engine Cycles: Gas Generator (GG) and Staged Combustion (SC)
- Return modes:
 - VTVL with retropropulsion landing on downrange barge (DRL) or with return-to-launch-site (RTLs)
 - VTHL with In-Air-Capturing (IAC) or autonomous return to launch site (Flyback)
- 2nd stage Δv of 6.6 km/s, 7.0 km/s
- Propellant Combinations: LOX/LH₂, LOX/LCH₄, LOX/RP-1

The design assumptions that were used to design the launchers which are presented herein are described in detail in [8] - [10]. Furthermore, those papers include the results for additional staging velocities and propellant combinations. For the limited scope of this paper, the most promising results were selected.

2.1 Operations

The operation of an RLV and its cost take up a greater share of the total launch costs compared to an ELV [12]. Hence, understanding the operational measurements for the aforementioned return strategies is essential to derive a

valid cost model. Nevertheless, the herein considered options differ in their operational requirements and additional hardware.

VTVL Downrange Landing/Return-to-Launch Site

The operational procedures which were adapted to the herein presented conceptual launchers were mainly derived from the SpaceX and Blue Origin approach [13]. Both methods were investigated considering required vessels, hardware and manpower. The personnel and workhours required were partially gathered from literature survey and partially from established cost models [13]. Thus, a reference mission profile was derived and applied to the conceptual launcher designs from [8].

Since the successful landing of the Falcon 9 first stage on the droneship “Of Course I Still Love You” in May 2016 the image of the SpaceX droneships is well known to the public (Figure 3, top right). However, landing and recovering a RLV stage in the sea and relocating it to the shore requires further hardware, vehicles and manpower. Considering downrange sea-going landings, two different approaches were identified. First, the well-known SpaceX approach with an unmanned barge with limited maneuvering capability. Second the recently revealed approach of Blue Origin to use a bigger as well as more flexible and agile vessel to land the stage.

In the case of the SpaceX method a landing barge with limited maneuvering capabilities is selected as landing platform (see Figure 3). For the recovery cost estimation in this paper, barges similar or close to the design of the SpaceX barges were assumed. These are mostly MARMAC typed barges which have to be modified (Figure 3, top right). For example, the barges require a positioning system which stabilizes the barge, devices to communicate with the approaching stage, structural reinforcements of the landing pad and hardware to secure the stage after landing. In this model, all ships were assumed to be owned by the RLV launching and recovering agency/company. However, the vessels could also be chartered or leased.



Figure 3: Ships considered for DRL: RoRo vessel bought by Blue Origin (top left). ASDS platform used by SpaceX (top right). Go Searcher and Go Navigator SpaceX supply vessels (bottom left). Hollywood tug boat used by SpaceX to tow the ASDS platform (bottom right). [13]

During a typical downrange landing mission the personnel responsible for post-processing, securing and transporting the barge with the landed stage are located on one to two supply vessels close by (Figure 3, bottom left). Furthermore, tugboats for tugging the barge from the landing site to the harbor are required (Figure 3, bottom right). A harbor mooring is necessary which allows for handling of the respective RLV stage. Furthermore, the stage has to be processed at the harbor which requires some kind of crane or lifting device, post-processing vehicles and transportation vehicles to transport the stage to the refurbishment/maintenance facility. In this work the total crew size of recovery operations (barge, supply vessel personnel, tugboat personnel) was set to 30 plus 16 extra workers at the harbor for loading and transportation [13]. This value assumes that the workers on the boat are not able to perform the tasks required in the harbor and consider a full occupancy of all accompanying boats. Advantages of the

SpaceX approach are the comparable low acquisition costs (1.5 million to 3 million US\$) and high flexibility due to redundancy in the fleet [13]. Major disadvantages are the high travel time (travel speed of 12 knots) and the relatively high number of vessels for one mission.

Blue Origin's approach to recovering the RLV stage differs slightly from the SpaceX approach. Contrary to the SpaceX barges with limited maneuvering capability that have to be towed, Blue Origin acquired a so-called RoRo ship (see Figure 3, top left). The idea is to land the stage on the modified ship's deck. Therefore, there is no need for towing boats and the number and size of supply vessels can be reduced. Compared to the SpaceX approach, the acquisition costs are higher (30 million to 40 million US\$) but the travel time can be reduced [13].

Considering an RTLS mission, the operational aspects are much less complex. The fact that the stage autonomously flies back to the launch site implies that no additional ships or vessels are needed. Instead, a simple landing platform which might consist of a concrete pad (compare with LZ-1 at Cape Canaveral) and communication devices can be sufficient.

VTHL In-Air-Capturing/Flyback

Similar to the VTVL downrange landing, the In-Air-Capturing method is considered a downrange "landing" method, where the landing occurs in-air with the successful capturing of the RLV stage. The then following tow-back to the landing site is comparable to the transportation of the VTVL stage on the barge back to the harbor. In analogy to the VTVL downrange landing an airborne vessel with the possibility of capturing and towing the approaching stage is necessary.



Figure 4: Possible aircraft for In-Air-Capturing and towing back winged RLV stages: the Airbus A340 (left) and the Boeing B747 (right) [2]

In this work, several second-hand commercial aircraft were deemed suitable for the task of catching and returning winged RLV stages, namely the B747-400, the B747-8F, the A340-400, the A380-800 and the A330 NEO (see Figure 4). Especially for the B747 aircraft a vast second-hand market exists and prices can vary depending on the aircraft's age and condition, the current market conditions and a range of other factors [13]. Second-hand B747-400 aircraft are available from 16 million to 32 million US\$ [13]. Additional modifications to the aircraft are necessary such as structural reinforcement at the load transmission points where the stage is connected to the aircraft and the installation of the capturing system. Those modifications and the connected costs were based on estimations of upgrading a commercial aircraft with an in-air refueling system or converting a passenger aircraft into a transport aircraft [13]. Furthermore, the aircraft should be remotely controlled due to safety reasons. Hence, the pilots would be seated in the mission control center where they would be in command of the aircraft. In this study, 3 pilots and 3 flight engineers were assumed to be necessary for the control of the aircraft.

The mission profile of an In-Air-Capturing mission for the aircraft consists of almost all typical phases of a commercial flight: engine start-up, taxiing, take-off, climb, cruise to the capturing site, waiting pattern until stage approach, IAC maneuver and stage capture, tow-back cruise, release, loiter, descent and landing and finally taxiing. Furthermore and similar to commercial operations, additional fuel is reserved to allow pre-landing waiting patterns and a trip to an alternative landing site. These mission phases were used to estimate the performance of the IAC aircraft and calculate the required trip time and fuel consumption [13]. The direct operating costs of aircrafts are then calculated by using well-known relations and cost models based on commercial aircraft operations.

Further hardware is required post-landing: the stage has to be depressurized and flushed of all remaining fuel/oxidizer residuals. Therefore, post-processing vehicles and manpower is needed at the stage's landing airport. The Space Shuttle for instance required around 150 of trained personnel and 25 vehicles to perform the required post-landing operations [14]. However, this system was manned and returning from orbital velocities. For the herein used VTHL reference launchers a reduced vehicle fleet of 8 and a total team size of 46 was assumed which was based on values from the FESTIP studies [13], [15].

Concerning facility costs the costs of building an adequate airstrip and hangar facilities were calculated. In reality however probably an already existing landing strip could be used or upgraded to allow the RLV stages to land.

Hence, in the cost model, the acquisition and maintenance costs of just the hangar and post-processing facilities on the airport were considered.

In the case of a flyback with turbine engines, no capturing aircraft is required. Hence, in accordance with the RTLS landings of the VTVL stages, the recovery operations are reduced to post-processing of the stage. Thus, the same assumptions as for the IAC mission apply without consideration of any operational aspects linked to the capturing aircraft.

2.2 Recovery, Refurbishment and Launch Cost Modeling

The cost of stage recovery and transportation are based on the assumptions explained in the previous section. Hence, the cost model philosophy is a “bottom-up” approach, meaning that each subsystem’s costs are estimated and the final costs are calculated by summing the individual expenses. In case of downrange landing and IAC the total costs of recovery of the RLV stage are composed of the cost elements from equation (1). In case of VTVL DRL, DOC_{Fleet} are the direct operation costs of the fleet, which include fuel costs and docking, navigation, cargo handling and berthing fees. The ownership costs include depreciation, interest and insurance rates, crew costs and maintenance and repair costs [13], [16]. Facility costs include the costs for cranes, additional harbor facilities and the costs of supply vessels. Finally, the costs of transportation of the stage to any post-processing facility are included. An overhead for management and mission control costs is added [13].

$$Cost_{recovery} = DOC_{Fleet,Aircraft} + Costs_{Ownership} + Costs_{Facilities} + Costs_{Transportation} \quad (1)$$

In case of a recovery mission for VTHL In-Air-Capturing stages, the direct operation costs of the capturing aircraft are composed of fuel costs, crew costs, ground handling, landing and navigation fees and maintenance costs. The ownership costs include depreciation, interest and insurance rates and facility costs include aircraft hangars, vehicle and additional infrastructure. In all recovery costs calculated within this work a distribution of all annual fixed costs over all missions per year was assumed. This rather commercial approach could be adapted and changed to a more governmental business case, where some costs (e.g. acquisition of airport...) might not be depreciated along the launch costs. However, to what amount which costs would be depreciated in reality is highly dependent on the business approach and the RLV’s shareholders and their interests.

As a comparison the costs evaluated with the recovery cost model established in this were compared with costs from the TRANSCOST model [12]. This model is using a “top-down” approach, meaning that no specific costs for subsystems are estimated. Instead, trends are derived from actual cumulated data about the costs of specific processes, systems and materials. This requires a sufficiently large database to use statistical methods to derive accurate trends. In the TRANSCOST model, those cost trends are based on historical such as recent launch vehicles. However, the database on operational or historic RLVs is much thinner compared to the data on ELVs, thus worsening the accuracy of a statistical “top-down” approach.

Other main drivers, if not the one with the biggest influence on RLV costs, are the refurbishment and maintenance costs. However, those costs are much more difficult to determine which was also experienced with the STS. The difficulty arises from the fact that any valid refurbishment and maintenance has to be based on knowledge about required work processes, man-hours, materials and facility and management overhead costs added by refurbishment. However, this requires knowledge of the necessary refurbishment processes which can only be accurately determined once a RLV stage was actually flown and the impact of the re-entry loads on the stage has been evaluated. SpaceX constantly upgraded the Falcon 9 throughout the years based on the experience gained by examining the recovered stages [4]. The DLR is currently following a roadmap of building subscale demonstrators of VTVL and VTHL launchers (respectively CALLISTO and ReFEx) and furthermore doing sophisticated analysis of re-entry loads and an estimation of their impact on the stage.

However, at the current state of the art at DLR, the refurbishment costs are not included in the cost estimations due to the very high uncertainties connected to determining refurbishment and maintenance costs. However, it is intended to include the determination of such costs in future work.

3. Technological Comparison

3.1 System, Masses and Performance

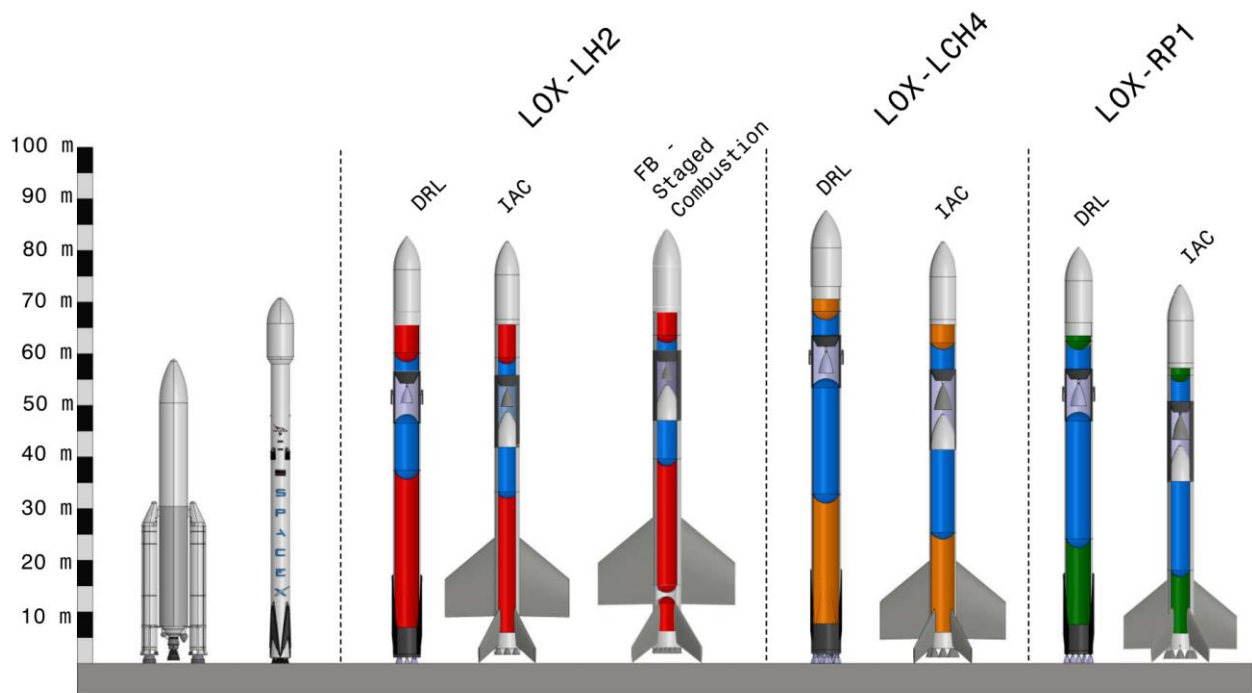


Figure 5: Size and Architecture of the conceptual launchers for VTVL - DRL, VTHL - IAC and VTHL - FB with an upper stage $\Delta v = 7$ km/s compared with the Ariane 5 and the Falcon 9 v1.2. LOX = blue, LH2 = red, LCH4 = orange, RP1 = green

Several of the conceptual RLVs using the VTVL and VTHL method with the mission and design assumptions from section 2 are shown in Figure 5. For the launchers shown in this picture the Δv of the second stage is equal (~ 7 km/s) for all designs. Generally, the launchers are larger compared to the Ariane 5 or Falcon 9. This is due to the high GTO performance (7.5 tons) combined with the TSTO architecture and the reusability of the first stage. The LOX/LH2 launchers are smaller and lighter compared to the hydrocarbon launchers which are about 2.7 times heavier in case of VTVL, and around twice as heavy in case of VTHL (see Figure 6). This came unexpected since the low density and high structural indices of the LOX hydrogen combination, although delivering a high specific impulse was expected to lead to bigger launchers. The reason for that is that the higher Isp in general requires less propellant mass. In case of the VTVLs, the higher Isp further requires less propellant mass for the descent maneuvers, thus in turn leading to a lower inert mass that has to be accelerated during ascent. This also explains the greater mass increase when switching from hydrogen to hydrocarbons as fuel in case of the VTVLs.

The second reason for the unexpectedly low mass and sizes of the hydrogen launchers is the ballistic coefficient. A low ballistic coefficient is favorable to reduce the re-entry loads and allow more deceleration by aerodynamic forces. The low bulk density of the LOX-LH2 combination leads to a higher ratio of launcher volume and thus area to mass, thus decreasing the ballistic coefficient. This is the case also for the VTHL hydrogen launchers which enables the respective stages to re-enter with lower aerothermal loads. Since in the VTHL conceptual design process the TPS is sized according to the loads experienced during re-entry, the TPS size and mass of the hydrogen launchers can be reduced accordingly.

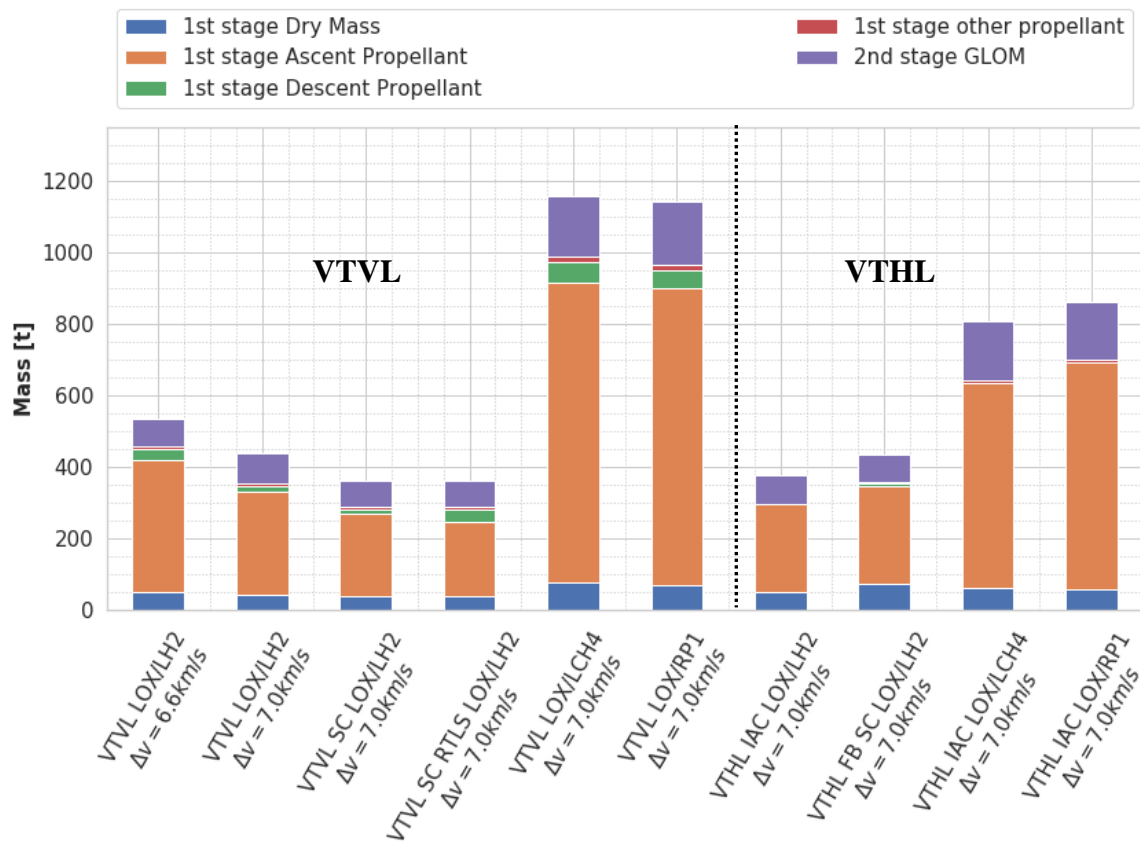


Figure 6: Mass breakdown of the conceptual VTVL-DRL, VTHL-IAC and VTHL-FB launchers

These effects explain the differences in size between the hydrogen and the hydrocarbon launchers. Interestingly, the winged vehicles are smaller than the VTVL vehicles. Obviously, this can be explained by the fact that VTVL launchers require more propellant and thus tank and propellant mass whereas the VTHL launchers mass increase is mainly in dry mass due to the wings, aerodynamic control surfaces and, in case of a flyback version, turbine engines. This trend can also be observed in Figure 7. Here, the structural indices and the inert mass indices of the first stages of the conceptual RLVs are depicted. The structural index is defined according to equation (2), with m_{dry} as the first stage's dry mass and $m_{propellant}$ as the total first stage propellant mass. The inert mass index is defined as shown in equation (3) where the inert mass m_{inert} includes all mass that is not contributing to the acceleration during ascent (e.g. descent propellant mass, dry mass, residuals and reserves).

It is clearly visible that the hydrogen launchers have a higher structural index than the hydrocarbons for all configurations. However, the structural index of the VTHL-FB configurations is the highest due to the high dry mass added by turbine engines, additional propellant and tanks, pumps, etc. The difference between inert mass index and structural index shows which component (dry mass, propellant) has more impact on the launcher's design. If the inert mass index is much higher than the structural index, the amount of propellant needed for the descent maneuvers has more impact on the launcher's performance. On the other hand, similar values for SI and inert mass index show that the dry mass is the main driver of the launcher's design and performance. In general, a high inert mass index leads to a lower performance and heavier launchers.

$$SI = \frac{m_{dry}}{m_{propellant}} \quad (2)$$

Furthermore, a clear advantage in mass can be seen, as expected, when switching to a staged combustion engine cycle due to the higher Isp. This leads to the lowest masses observed throughout the whole launcher range. However, the development and production of a staged combustion engine is more complex and thus more costly compared to gas generator engines. As this can only be reflected in a valid cost model it has to be taken into account in future work.

Another interesting observation one can draw from the data shown here is the fact that a lower upper stage Δv of 6.6 km/s leads to a higher GLOM and a slightly higher inert mass index. This can be explained by two reasons; first, the first stage Δv is higher and thus the propellant amount increases. Second, the re-entry loads increase due to a higher

velocity at MECO and thus re-entry velocity. These points once again emphasize the importance of the re-entry loads on the launcher design, which will be discussed in more detail in the following section.

$$\text{Inert Mass Index} = \frac{m_{\text{inert}}}{m_{\text{propellant}}} \quad (3)$$

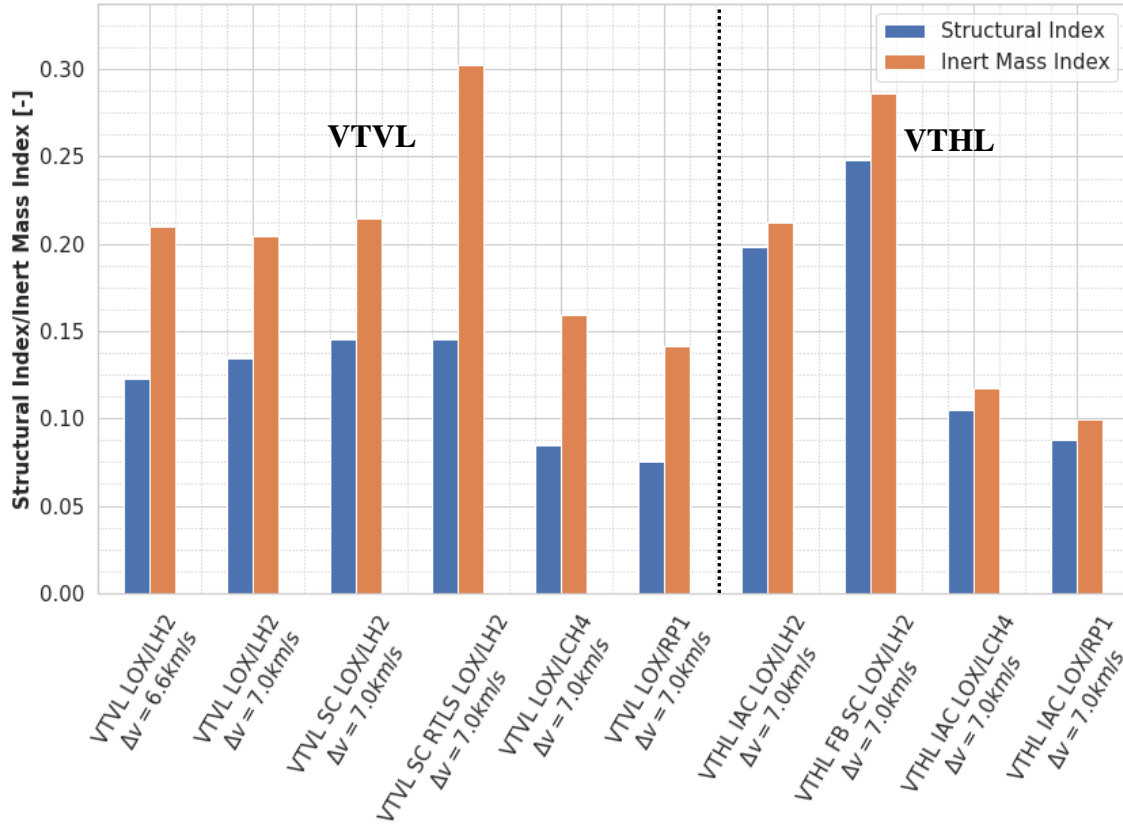


Figure 7: Structural Indices and Inert Mass Indices of the first stages of the conceptual VTVL-DRL, VTHL-IAC and VTHL-FB launchers

3.1 Re-entry Trajectory & Loads

Figure 8 shows the re-entry trajectories of the conceptual launchers such as the trajectory of the Falcon 9 of the SES 10 mission. It is important to note that this trajectory was not officially published by SpaceX but rather reconstructed using reverse-engineering methods at DLR [4]. The plot further shows the isolines for different heat flux and dynamic pressures. The heat flux values refer to the stagnation point heat flux according to a modified Chapman equation as shown in formula (4). Here, ρ is the local density at the respective altitude according to the US standard atmosphere 1976, ρ_R is a reference density value of 1.225 kg/m³, $R_{N,r}$ is reference nose radius (here 1 m), R_N is the vehicle nose radius (here 0.5 m for all vehicles), v is the vehicle's velocity and v_R is a reference velocity of 10000 m/s.

$$\dot{q} = 20254.4 \text{ W/cm}^2 \cdot \sqrt{\frac{\rho}{\rho_R} \frac{R_{N,r}}{R_N}} \left(\frac{v}{v_R}\right)^{3.05} \quad (4)$$

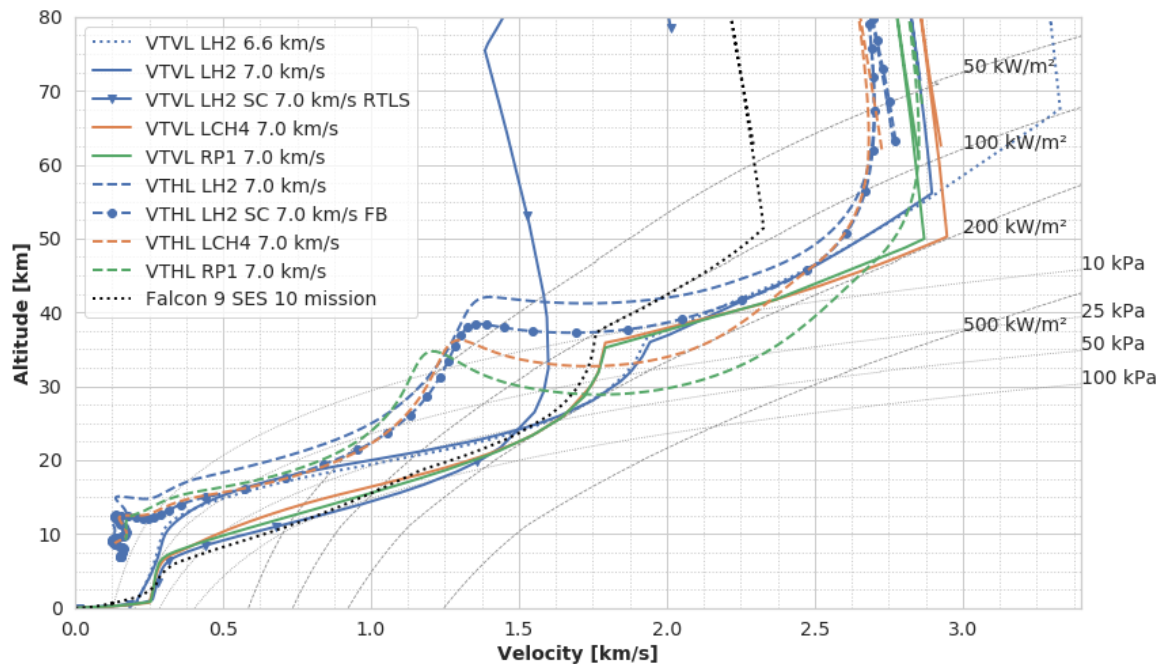


Figure 8: Re-entry trajectories of the conceptual VTVL-DRL and VTHL-IAC launchers and the Falcon 9 re-entry trajectory of the SES 10 mission

The deceleration of the VTVL launchers is achieved via a re-entry burn which occurs between 50 km and 67 km in altitude. In case of an RTLS mission this burn occurs at higher altitudes due to the steeper re-entry at lower velocity. This burn is characterized by the sudden change in velocity gradient. Contrary to that, the VTHL launchers have a more gradual deceleration profile. In the re-entry trajectory profile it can be clearly seen that the VTVL launchers follow a more or less similar velocity-altitude profile due to the fact that a heat flux of 200 kW/m² and a maximum dynamic pressure of 200 kPa were set. The former value was based on the SpaceX SES 10 mission trajectory which experienced a similar maximum heat flux (see Figure 8). The VTVL trajectories lie quite close to the 200 kW/m² isoline from re-entry until around 1.5 km/s. Interestingly, the hydrocarbon launchers experience the first heat flux peak shortly before the begin of the re-entry burn whereas the hydrogen launchers only get close to the 200 kW/m² mark during the aerodynamic flight. This can be explained by the lower ballistic coefficient of the hydrogen stages and the lower gradient of velocity reduction through the re-entry burn. This combination is of advantage for the fuel consumption during the re-entry, since more velocity can be shed by aerodynamic forces. Higher loads are generally experienced for the GTO missions with downrange landings, since the velocity at MECO is the highest for high-energetic target orbits. This explains the relatively low loads of the RTLS mission with much lower MECO velocity due to the fact that more propellant is needed for the descent maneuvers and is thus not available for the acceleration during ascent. The flight path angle is much higher, since a steep velocity reduces the horizontal velocity component of the velocity vector.

For the VTHL launchers, no specific boundary conditions for heat flux or aerodynamic pressure were set. Instead, the acceleration in z-body axis is limited to a value of 3.5 g. The TPS is sized to withstand the experienced heat flux during the re-entry mission. This explains why the VTHL trajectories differ in their velocity-altitude profile. Once again, the ballistic coefficient plays a major role in the loads experienced; a low ballistic coefficient, e.g. for hydrogen stages, allows to decelerate the vehicle in higher altitudes which significantly reduces the heat flux and thus the TPS mass. During the final phase of the re-entry, the VTVL launchers obviously experience higher dynamic pressure, since their terminal velocity is higher compared to the VTHLs.

Figure 9 shows the Δv breakup and budget of the VTVL and VTHL launchers of the re-entry trajectory. All positive values lead to acceleration of the vehicle, all negative values decelerate the vehicle. Hence the sum of all values is equal to the actual velocity reduction from the beginning (MECO) until the end of the re-entry trajectory calculation. The plots don't contain losses by thrust vectoring which are not available in the presented 3-DOF trajectories. As expected, the Δv is reduced by engine burns and drag in case of the VTVL and just by drag in case of the VTHL. Interestingly, the Δv reduced by aerodynamic drag is higher than the Δv by engine burns for all downrange landing missions of the VTVL. Only in case of an RTLS mission, the velocity reduction by engine burns is higher due to the fact that returning to the launch site requires significantly more Δv .

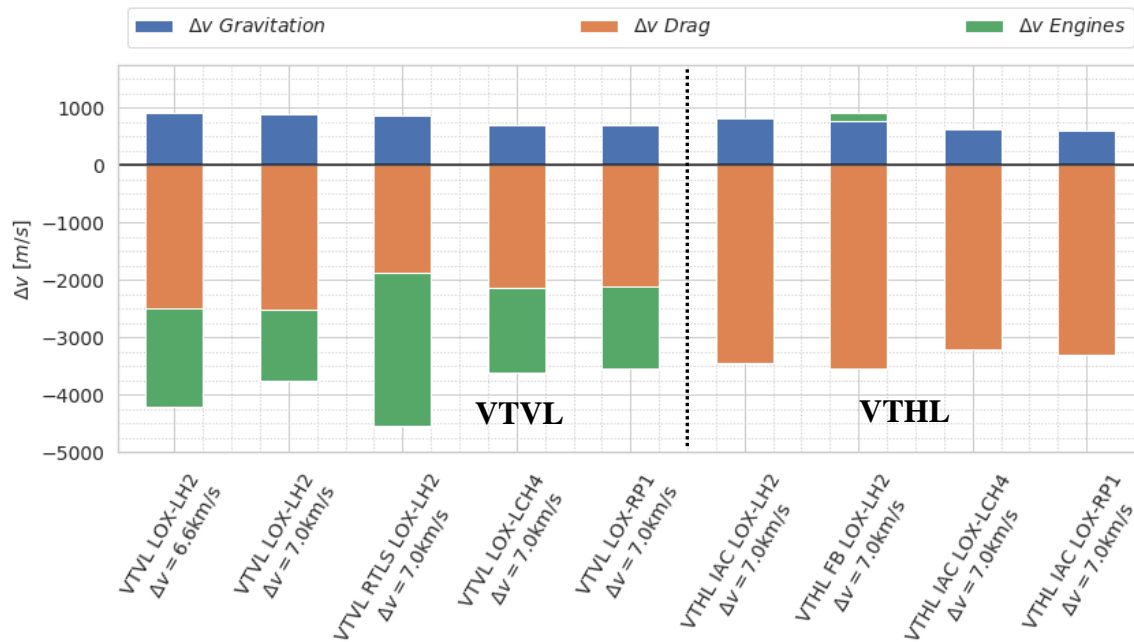


Figure 9: Δv Budget of the re-entry trajectories of the conceptual VTVL and VTHL launchers with an upper stage Δv of 7.0 km/s

The Δv added to the vehicle's velocity by gravitation is a product of flight time and flight path angle (similar to the gravitational losses during ascent). A vertical approach leads to higher gravitational losses, hence explaining the quite low gravitational Δv of the VTHL due to the fact that their re-entry trajectory is generally flatter. In case of the VTVL launchers the gravitational Δv is lower with less flight time.

In summary, the VTVL launchers have to manage the aerothermal loads during re-entry by timing and duration of the burns. The necessary Δv can be reduced by lowering the ballistic coefficient. The timing however is dependent of the propellant combination chosen, the velocity during re-entry, the available thrust, the maximum allowable heat flux and the ballistic coefficient. Low ballistic coefficients and high specific impulse propellants lead to lower propellant mass for the descent maneuvers. This in turn reduces the required ascent propellant and thus the total launcher size, which explains the large advantage of hydrogen observed in Figure 5.

Similarly, the VTHL launchers favor the high Isp propellant combination LOX/LH2. As for the VTVL launchers the ballistic coefficient plays a major role in reducing the vehicle mass. The lower the ballistic coefficient, the lower are the re-entry loads and thus the TPS mass. This reduces the launcher's dry mass which leads to the same effect as observed for the VTVL launchers: a decrease in GLOM.

4. Economic Comparison

The economic impact of the recovery operations was estimated by using the assumptions as described in section 2.1. A launch rate of 15 launches per year was assumed. The economic conditions are given in US\$ related to the economic conditions in 2018 [13]. In Figure 10 all costs related to recovery are presented. In case of the IAC, two different aircraft were used: the B747-400F with 4 engines and the A330-300 NEO with 2 engines. As reference RLV stage a ~50 ton conceptual launcher is assumed. However, the impact of the RLV mass on the aircraft's DOCs is negligible since the share of DOCs to total recovery costs is small. For the VTVL approach, the SpaceX DRL method was compared with the Blue Origin DRL method (see section 2.1 for details). As a reference stage a 45 tons VTVL conceptual launcher was selected. Similar to IAC, the impact of the mass on costs is negligible and the MARMAC barges are rated for much higher loading anyways.

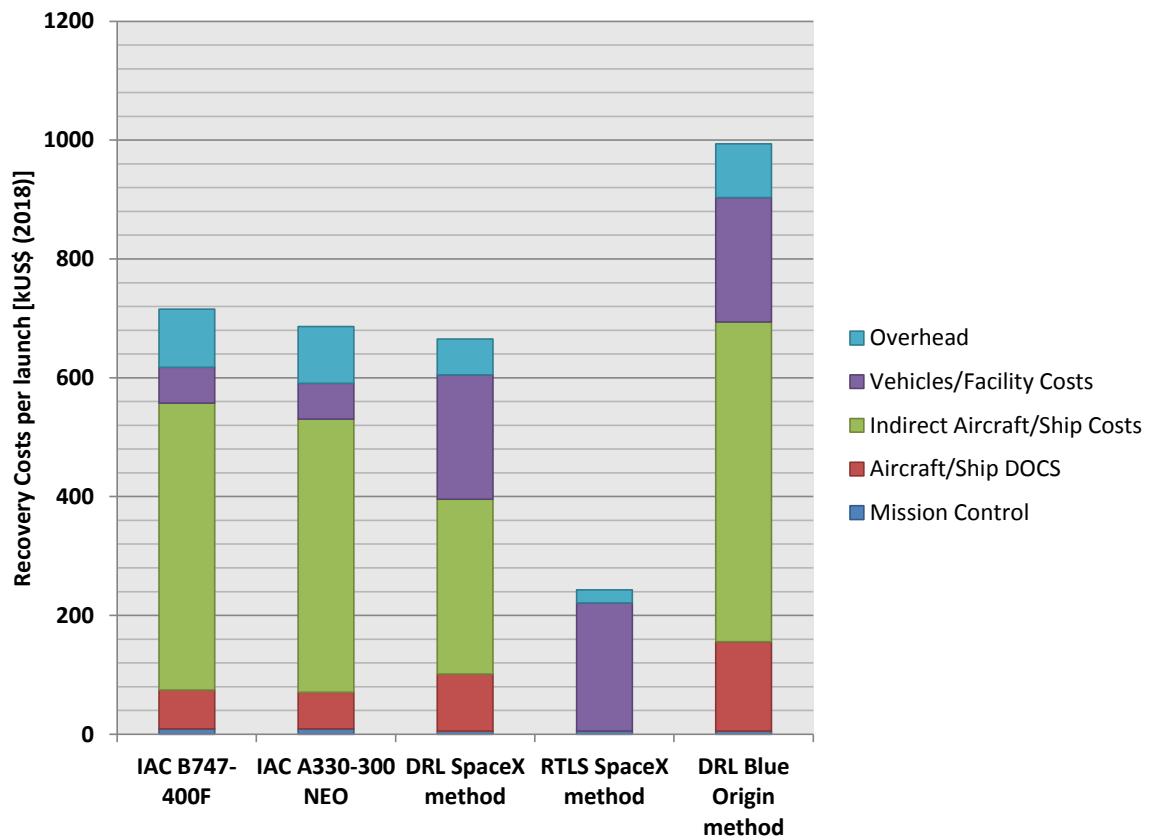


Figure 10: Recovery Costs for In-Air-Capturing with the B747-400F and the A330-300 NEO compared to DRL with the SpaceX method, DRL with the Blue Origin method and RTLS

The total recovery costs of the IAC are mainly composed of indirect costs related to the aircraft. This is due to the fact that the relatively high acquisition and interest costs of the aircraft are depreciated over its whole estimated lifespan (15 years in this case). The DOCs including landing fees, fuel costs and crew costs are quite low in comparison. This is due to the quite low mission time of ~6 hours. The fuel costs are 66% of the aircraft's DOC, in the case of the B747 around 42000 US\$ (2018 EC). The low DOCs are further explained by the fact that the remote control crew is only paid for the actual "mission time" of 6 hours. In reality, a remote control crew would be hired and paid annually.

The costs of recovery by ship (DRL) are comparable to IAC costs when choosing the SpaceX method with a larger fleet of smaller ships. However, here the indirect ship costs (including crew costs here) are lower due to the lower acquisition price of such barges. The direct costs are higher mainly due to the longer mission time (~ 6 days). Facility costs are high since the acquisition of a lifting device (e.g. crane) was assumed in this business case. Comparing the SpaceX method with the Blue Origin method (small fleet with large ship) shows some disadvantages for the Blue Origin method which are only due to the high price of the big RoRo ship and the higher fuel consumption. The RTLS method is, as expected, the cheapest possibility to recover stages since the costs related to the recovery vessel are falling away.

In general, the costs of recovery operations are around 230 kUS\$ for RTLS, 650 kUS\$ (SpaceX) to 1000 kUS\$ (Blue Origin) and around 700 kUS\$ - 720 kUS\$ for the IAC recovery per launch for a launch rate of 15 launches per year. It is important to note that only the recovery is considered, no refurbishment or maintenance costs. The costs added by recovery are not considerably high which show that, within the assumptions used in this work, the recovery aspect of reusing stages has a minor impact on the total launch costs of a launch vehicle. Furthermore, it is important to note that the recovery costs are dependent on the launch rate. A high launch rate leads to lower recovery costs since the fixed costs are distributed over a higher number of launches. Figure 11 shows this trend for the recovery methods calculated with the cost assumptions used in this work versus the cost formulas from TRANSCOST. The trend of decreasing launch costs for all methods is clearly visible. For a high launch number, both the DRL SpaceX method and the VTHL IAC method have comparable recovery costs.

The costs calculated with the TRANSCOST model are, especially for high launch rates, considerably higher. The reason for that is that the TRANSCOST model is based on other cost data and assumptions than the model used in this work. However, the TRANSCOST model is expected to over predict the VTHL recovery costs since they are

based on a manned system with relatively low launch rates (Space Shuttle). The VTVL model is based on theoretical studies of such launchers. As such, the accuracy is questionable too.

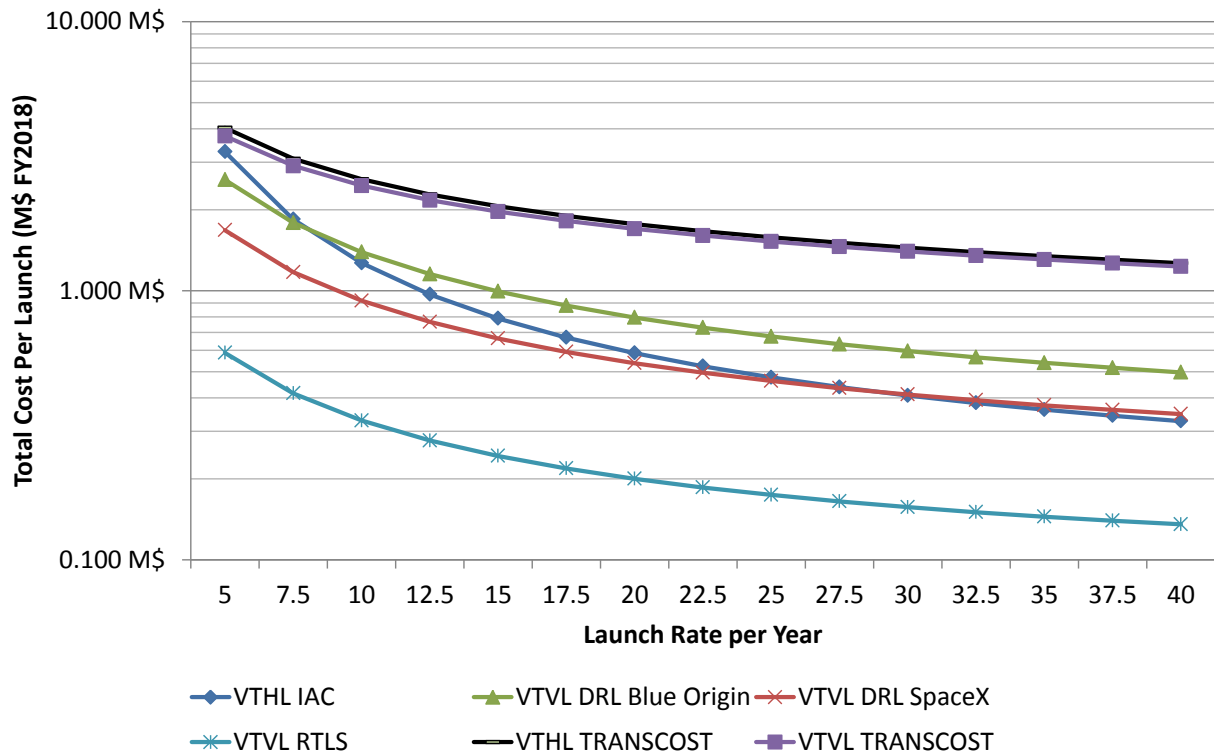


Figure 11: Recovery Costs per Launch in MUS\$ (EC 2018) for different recovery methods and launch rates

In conclusion, the costs obtained with the recovery cost model presented in this work allow for a quantitative assumption of the recovery costs. As with all cost models the problematic is that the results are dependent on the assumptions that are input into the cost model. However, since the model presented within this work used a “bottom-up” approach with a more hardware and personnel –focused approach using validated cost models for some of the recovery systems, the results allow a discussion and comparison with other cost models. Nevertheless, operational costs are only one part of the whole equation of reusing stages; the other great pillar of RLV costs is refurbishment and maintenance costs. The estimation of those costs shall be enhanced in future work.

5. Conclusion and Outlook

The AKIRA project allows comparing different methods and approaches of introducing reusability to launch vehicles. In this work, this comparison was performed for four different methods: VTVL-DRL, VTVL-RTLS, VTHL-IAC and VTHL-FB. The comparison was performed on different levels. First, technological aspects such as performance, system design, mass, re-entry loads and re-entry load handling were evaluated. Second, the economic and operational aspects were assessed.

Considering the comparison on technological level, several interesting results could be derived. Considering the propellant combination it is of advantage to choose a hydrogen-oxygen combination for any RLV from a strict performance driven point-of-view. This propellant combination allows the lowest system mass due to a high Isp, low structural masses and thus ballistic coefficients and hence low re-entry loads. However, from a system point-of-view several drawbacks arise from this combination: first, the handling of hydrogen is more complex than the handling of hydrocarbons. A cryoinsulation is required in any case which requires a sophisticated design of the TPS and cryoinsulation in case of the VTHL launchers [2], [3]. Furthermore, the engines are subject to higher thermal loads and thus require a sophisticated design to ensure multiple reuses are possible.

Comparing VTVL and VTHL launchers to each other, the differences in design get visible. The GLOM of VTVL launchers is higher when using the same propellant combinations. This is explained by the demand of descent propellant in case of the VTVLs which in turn increases tank volume and mass, too. The deceleration of the VTHL launchers is caused by aerodynamic forces only.

Thus, different design demands arise for both methods. The main driver of VTVL design is finding a design point where the balance between separation velocity, ascent and descent propellant and upper stage Δv shows the lowest total system masses and bearable re-entry loads. In the case of VTVL launchers, it is advantageous to tend to lower separation velocities of the first stage. However, considering that this decreases the share of reused to expended hardware from an economic point-of-view, the optimum will have to be found considering both technical and economic viewpoints. Similarly, the VTHL launchers require a balanced design between wing mass and area, re-entry loads, ballistic coefficient and thus total system mass. While a greater wing area reduces the re-entry loads, the system mass increases and thus the performance decreases.

For both methods viable design points can be found where their respective advantages arise. The VTVL method allows more flexibility considering different target orbits by simply changing the ratio between ascent and descent propellant according to the target orbit, the payload mass and the return method (DRL vs. RTLS). Thus, different return modes can be performed by the same launcher. In contrary, a VTHL is either designed as Flyback version or IAC version. The return mode profile cannot be adapted to the payload mass.

However, the advantage of the VTHLs is the lower impact of reusability on the launcher's performance. The increase in inert mass by using the VTHL method is less than the increase in inert mass of the VTVLs. Thus, the same performance can be achieved with a lighter and smaller vehicle.

This comparison shows the necessity to assess RLVs on an economic level, since the technical comparison alone doesn't allow final conclusion. Also, the economics are the main driver of any launch vehicle, especially in the context of RLVs that have to be able to lower the launch costs compared to an ELV to justify the additional development and operational effort. Hence, an assessment of operational scenarios including recovery procedures, hardware, personnel and facilities was performed in this work to determine the impact of recovering stages on the launch costs.

This analysis led to the conclusion that the costs of recovery operations can be kept within reasonable limits for all return modes. Comparing IAC with DRL shows comparable launch costs which are in the range of 800 kUS\$ to 1000 kUS\$ per launch for a launch rate of 15 launches per year. Considering the total launch costs of launch vehicles those costs are a comparable small share of the total launch costs. Nevertheless, these conclusions are drawn from the assumptions used within this model which is subject to improvement and enhancement in the ongoing work of AKIRA.

Finally, the total launch costs including refurbishment and maintenance cost should be taken into account to allow for a comparison of RLV methods on all levels. This step is the most difficult to assess at the current state-of-the-art in Europe. However, future work shall use knowledge gathered from other DLR projects such as ReFEx [5], CALLISTO [11] and XTRAS [8] - [10] to enhance the understanding of the impacts of re-entry loads on structure and critical parts of the RLV stage. This shall lead to a better estimation of costs in future works.

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