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Systematic Assessment of Reusable First-Stage Return Options

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Interest in the reusability of rocket-powered first stages for orbital launch vehicles has strongly increased since the successful demonstration of a Falcon 9 booster re-flight in March 2017. The technology chosen by SpaceX is one feasible option, however, not necessarily the optimum one for each application and operational scenario.

The paper compares the characteristic flight conditions of winged gliding stages with those of rocket-decelerated vertical landing vehicles. The focus is on the atmospheric reentry and potentially the return to launch site with evaluation of loads (dynamic pressure, accelerations, heatflux) and necessary propellant as well as dry mass.

Keywords: RLV, TSTO, trajectory, LOX-LH2-propulsion, SpaceLiner, Falcon 9, LFBB, in-air-capturing

Nomenclature

D	Drag	N
I_{sp}	(mass) specific Impulse	s (N s / kg)
L	Lift	N
M	Mach-number	-
T	Thrust	N
W	Weight	N
g	gravity acceleration	m/s^2
m	mass	kg
q	dynamic pressure	Pa
v	velocity	m/s
α	angle of attack	-
γ	flight path angle	-

Subscripts, Abbreviations

AOA	Angle of Attack
CAD	Computer Aided Design
DOF	Degree of Freedom
DRL	Down-Range Landing site
ELV	Expendable Launch Vehicle
GLOW	Gross Lift-Off Mass
IAC	In-Air-Capturing
LEO	Low Earth Orbit
LFBB	Liquid Fly-Back Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
SRB	Solid Rocket Booster (of Space Shuttle)
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control
VTHL	Vertical Take-off and Horizontal Landing
VTL	Vertical Take-off and vertical Landing
CoG	center of gravity
cop	center of pressure

1 INTRODUCTION

Complex, high-performance, high-cost rocket stages and rocket engines are disposed today after a short operating time. Used components are falling back to Earth, crashing on ground or into the Oceans. Returning these stages back to their launch site could be attractive - both from an economical as well as an ecological perspective. However, early reusability experience obtained by the Space Shuttle and Buran vehicles demonstrated the challenges of finding a viable operational case.

Systematic research in the different reusability options of space transportation is urgently needed to find the most promising concept. A system analysis approach is capable of successfully addressing all key-aspects, mainly finding a technically feasible design for which the performance impact of reusability can be assessed. Non-linear dependencies of multiple-disciplines demand iterative numerical design and simulations. A fast, multi-disciplinary Reusable Launch Vehicle (RLV) pre-design approach is necessary for generating reliable datasets for the evaluation.

The systematic research needs to address first the different possible return modes for different separation conditions of reusable stages. Strongly diverging characteristic flight conditions and loads can be identified after MECO which have a significant impact on cost and operations of the RLV.

1.1 The historic flight 32 of Falcon 9

Falcon 9's SES-10 mission into GTO on March, 30th 2017 (Figure 1) marked a historic milestone on the road to full and rapid reusability as the world's first reflight of an orbital class rocket booster [1]. The booster stage called B1021 was first used in the CRS-8 mission in April 2016 and was the first Falcon 9 booster ever that had successfully been landed on a droneship. In the 11 months passed between both launches the first stage underwent extensive refurbishment and testing.

Following stage separation, Falcon 9's first stage successfully performed a landing on the "Of Course I Still Love You" droneship stationed downrange in the Atlantic Ocean.

Figure 1: Lift-off of F9 FT at LC-39A and landing of its first stage on March 30th, 2017 (Courtesy https://www.flickr.com/photos/spacex)

Extensive studies of the SpaceX launcher Falcon 9 and several of its actually flown missions have been performed at DLR to gather a better understanding of the impact of a non-winged VTL on the launcher's performance based on actually flown missions. Results presented in [3] show a good accordance of the actual trajectory from the webcast data and the simulated trajectory of DLR.

Previously, Blue Origin had already achieved successful recoveries and reflights of its rocket-powered first stage of the New Shepard vehicle. These missions, however, were all suborbital with a maximum apogee slightly above 100 km. Therefore, the stages are subject to different loads and performance requirements.

The technical approaches of SpaceX and Blue Origin are similar with vertical take-off and vertical landing (VTL) of the reusable stages. Despite the fact that this is obviously a feasible and potentially promising option, several other methodologies of the first stage's reentry and return exist. The currently chosen approach in the USA is not necessarily the optimum one for each application or different operational scenario.

An interesting comparison of *various methods for recovering reusable lower stages* with focus on US and Soviet/Russian launcher concepts has been published in 2016 [4]. A systematic analysis and assessment of the reusable first-stage reentry and return options is now investigated by DLR-SART in a European perspective.

2 STUDY LOGIC AND ASSUMPTIONS

The ultimate criterion for the evaluation of RLV first-stage-concept's economic interest is a reliable cost estimation including as a minimum manufacturing, operations, maintenance, and infrastructure expenses. However, today only a very tiny, limited amount of such cost data has been attained by the preparation of the 2 successful reflights of Falcon 9 boosters. This data, not publicly available, obviously, is insufficient to establish an empirically based RLV-operations cost model. Therefore, at the moment nobody in the World is capable of giving any reliable quantified prognosis on the actual cost structure for different types of RLV.

This said, the situation is anything but completely hopeless. At least in theory, RLV offer a huge launch cost advantage compared to ELV. However, the inherent performance loss by bringing used stages at high speed back to Earth as well as additional refurbishment and potentially infrastructure expenses are degrading this theoretical advantage. The actual detriment of reusability is strongly depending on the technical RLV-architecture chosen which is influencing system inert mass as well as mechanical and aerothermal loads with an impact on component lifetime. Both, masses and flight loads, can be assessed with much higher accuracy than cost by using preliminary design methods. Thus, it is possible to distinguish with good level of confidence between promising design options and less favorite choices.

The paper compares the characteristic flight conditions of winged gliding stages with those of rocket-decelerated vertical landing vehicles. The focus is on the atmospheric reentry and potentially the return to launch site with evaluation of loads (local heatflux in critical areas, dynamic pressure, accelerations) and necessary propellant as well as dry mass.

2.1 Mission assumptions

All presented RLV-configurations in this paper are assuming similar key mission requirements:

- GTO: 250 km x 35786 km
- Launch site: CSG, Kourou, French Guiana

The vehicles should be capable of performing secondary missions to LEO, MEO or SSO. Loads and performance data presented in this systematic assessment, however, are restricted to the GTO-mission for the sake of better comparability.

The design payload target of several of the investigated configurations is 7000 kg to GTO with an additional project margin of 500 kg. Some RLV aim for different, higher payloads with minor impact on the results presented here.

2.2 Configuration assumptions

The investigated RLV first stage configuration types are much different in their aerodynamic and mechanical lay-out as well as in their return and landing modes. One common element is the conventional vertical lift-off, offering significant advantages for rocket-powered vehicles.

The potential RLV stage return modes strongly vary from pure ballistic to using aerodynamic lift-forces, gliding flight or captured towing. In case of propelled return, the options stretch from using the rocket engines or separate air-breathing turbo-fan or even propeller for efficient low-speed flight. A schematic of the available options is presented in Figure 2 which considers also the possibility of returning only some key-components of the first stage while discarding other elements. Recovery of merely the propulsion bay with the main rocket engines has been proposed recently for ULA Vulcan [10] and another concept under the name Adeline.

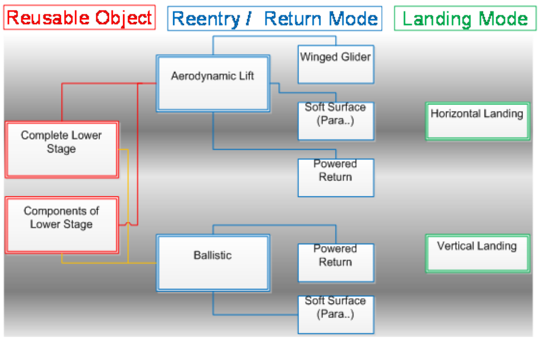

Figure 2: Potential RLV stage return modes

The option-branches as shown in Figure 2, although already quite diverse, are to be further subdivided if different propellant combinations as well as different staging Mach numbers are to be considered. In order to limit the amount of data, for the study presented here, the investigated RLV-options have been restricted to the return of *complete* stages with fixed wings or non-winged architectures comparable to the Falcon 9 booster. Figure 3 gives an overview of the classification implemented. The reusable stage's aerodynamic shape is influencing the landing as well as the return options. A wing attached to the fuselage or tank structure has to generate lift force as its main purpose. Aerodynamic control devices as found on a ballistic reusable stage like the Falcon 9 are understood as similar to control flaps but with minimum lift contribution.

While the non-winged type has no capability of soft horizontal aerodynamic landing, the winged RLV-stages in most cases are designed for a conventional horizontal runway touch-down. However, a specific type with relatively small wing area used in high-speed reentry might switch to vertical powered landing afterwards.

Four different return modes are considered:

- RTLS: autonomous rocket-powered return flight (similar to some Falcon 9 missions back to Cape Canaveral),
- DRL: down-range landing; in case of Kourou-missions only on sea-going platform ("barge") which subsequently brings the stage back to the launch site,
- LFBB: autonomous airbreathing-powered return flight at subsonic speed,
- IAC: capturing in flight the winged unpowered stage with an aircraft and towing it back for an autonomous landing in gliding flight.

A technical description of the return modes is provided in the following section 2.3.

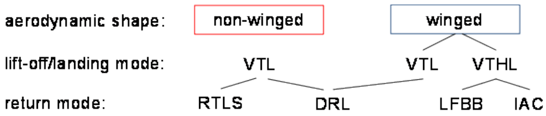

Figure 3: Investigated RLV stage return modes

Alternative return and landing modes are *not* considered because they are not compatible with the mission requirement or provide too small contribution to the overall Δ-v. Soft lift surfaces like parachute or parafoil are not well-suited for landing masses beyond 30 tons. Further, their landing accuracy is poor making them best suited for dropping the stage into an ocean [4] like it was done with the Space Shuttle's SRBs. Simple glide-back stages are restricted to separation Mach-number of approximately 3.

Two-Stage to Orbit (TSTO) and Three-Stage to Orbit architecture concepts are included. The propellant types are all cryogenic, stretching from the high energetic but relatively low density LOX-LH2 to the hydro-carbon combinations LOX-LCH4 and the potentially innovative propane LOX-LC3H8 [3]. Further, the same propellant combination has been assumed in all main stages of the selected configurations although this is not a per-se requirement and different propellants could be chosen for different stages.

2.3 Return modes description

2.3.1 Rocket-powered return flight (RTLS)

In this mode main rocket engines on the reusable stage are used not only for deceleration and vertical landing but usually in an additional firing to achieve the autonomous return of the stage to the landing field on or close to its on-shore launch site. SpaceX succeeded for the first time in bringing the booster stage back in December 2015, even before successful touchdown on a droneship. A dedicated landing zone called LZ-1 has been constructed for this purpose in Cape Canaveral, Florida (Figure 4). This approach is used in low-performance, LEO missions of Falcon 9, e.g. the CRS-flights for NASA to the ISS. In general, this return mode is more suitable in case of lower separation- or MECO-Mach-numbers and in moderate distance to the launch site because of the otherwise excessive amount of fuel needed by the rocket engines.

Figure 4: Landing of F9 FT first stage on LZ-1, X-37B mission, September, 7th 2017 (Courtesy https://www.flickr.com/photos/spacex)

2.3.2 Down-range landing (DRL)

Landing a used stage down-range of its launch site is probably the most straight-forward idea and thus has been proposed several times already in the past. However, the particular challenge is related to the fact that suitable natural down-range sites are very scarce if existing at all. An artificial sea-going platform or ship is offering significantly more flexibility to the missions and has been adopted by SpaceX for the Falcon 9 high performance missions (Figure 5). The performance loss of a launch vehicle applying the DRL-method is reduced compared to one using the RTLS mode.

Figure 5: Sea-going platform ("barge" or "droneship") of company SpaceX (Courtesy https://www.flickr.com/photos/spacex)

The sea-going platform should be capable of delivering the landed stage back to a sea-port close to the launch site and, therefore, needs to be a sea-going ship. The approximate size of the SpaceX' droneships is not small: 91 m by 52 m. The SpaceX platform needs additional tugboats towing it back typically within 4 to 5 days to the Cape Canaveral port. Further, depending on the port location, substantial ground transportation equipment is required for moving the stage to the refurbishment site. Overall, the better performance of DRL compared to RTLS is paid for by additional infrastructure investment and operations cost.

Theoretically, the DRL-mode is independent of vertical or horizontal landing. In practice even large (and expensive) aircraft carriers are probably too short and too narrow to allow landing of a winged RLV. Therefore, in this investigation DRL is linked to VTL-configurations.

2.3.3 Autonomous airbreathing-powered fly-back (LFBB)

The classical method of bringing reusable first stages back to their launch site in autonomous flight is using a separate airbreathing cruise propulsion system. The approach was popular in the 1980s up to the early 2000s. Famous examples are studies on a second generation Soviet Energia Buran [4, 16], the derived Baikal or in late 1990s studies on potential Space Shuttle upgrades intending the replacement of the SRB [11]. In Germany the ASTRA study investigated such LFBB [12] as shown in Figure 6 as an Ariane 5 modernization option.

Figure 6: LFBB of ASTRA-study in artists' impression at separation from expendable core [12]

The interest in the LFBB approach originates from the fact that turbofans in subsonic cruise flight are at least ten times more efficient than rocket engines using the same fuel. Thus, the fly-back propellant, inert mass during ascent, should be significantly reduced.

In the ASTRA concept, typical for LFBB, three turbo engines without afterburner using hydrogen have been foreseen for the stages' fly-back. The feasibility of replacing kerosene by hydrogen in an existing military turbofan (EJ-200) investigated within the ASTRA-study shows the engine is capable of continuous operation with hydrogen fuel under all LFBB attitudes and manoeuvre loads [13, 14]. Such an additional propulsion system is adding some complexity to the RLV while components accommodation – at least for the ASTRA LFBB – is not an issue (Figure 7).

On the downside, the LFBB-mode in any case adds the secondary propulsion system mass and is not feasible without a sufficiently large wing allowing cruise flight at acceptable L/D.

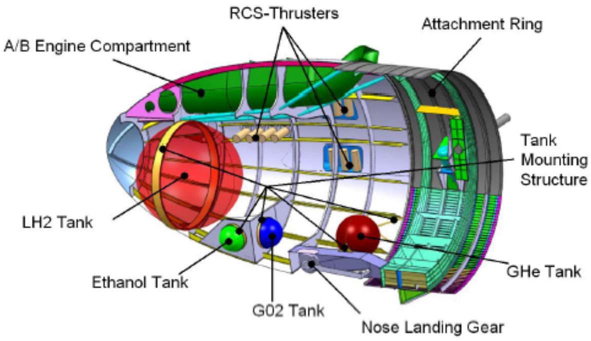

Figure 7: Integration of turbofan engine and auxiliary tank in nose of ASTRA LFBB [14]

2.3.4 "in-air-capturing" (IAC)

Techniques of powered return flight like LFBB obligate an additional propulsion system and its fuel, which raises the stage's inert mass. The patented "In-air-capturing" [5] offers a different approach with better performance: The winged reusable stages are to be caught in the air, and towed back to their launch site without any necessity of an own propulsion system [6]. The idea has similarities with the DRL-mode, however, initially not landing on ground but "landing" in the air. Thus, additional infrastructure is required, a relatively large-size capturing aircraft. Used, refurbished and modified airliners should be sufficient for the task.

After DLR had patented the "in-air-capturing"-method (IAC) for future RLVs, two similar approaches have been proposed. However, those named *mid-air retrieval* or *mid-air capturing* are relying on parachute or parafoil as lifting devices for the reusable parts and helicopters as capturing aircraft. The first proposal was made by the Russian launcher company Khrunichev [9] and the most recent one by the American company ULA for its newly proposed Vulcan launcher. A parachute and helicopter based system is obviously less flexible and significantly less robust than the in-air-capturing based on winged RLV and winged aircraft. Consequently, the ULA proposal intends recovering not more than the first stage's engine bay instead of a full stage [10].

A schematic of the reusable stage's full operational circle is shown in Figure 8. At the launcher's lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable winged stage is separated from the rest of the launch vehicle and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Differently, within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft (most likely fully automatic and unmanned), offering sufficient thrust capability to tow a winged launcher stage with restrained lift to drag ratio. Both vehicles have the same heading still on different flight levels. The reusable unpowered stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles, but can be extended up to about two minutes. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m [7]. After successfully connecting both vehicles, the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released, and autonomously glides like a sailplane to Earth.

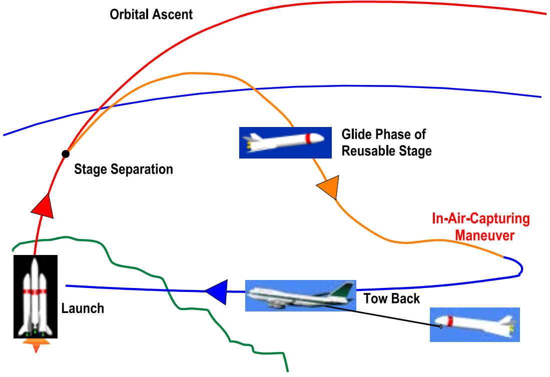

Figure 8: Schematic of the proposed in-air-capturing

The selected flight strategy and the applied control algorithms show in simulations a robust behavior of the reusable stage to reach the capturing aircraft. In the nominal case the approach maneuver of both vehicles requires active control only by the gliding stage. Simulations (3DOF) regarding reasonable assumptions in mass and aerodynamic quality proof that a minimum distance below 200 m between RLV and aircraft can be maintained for up to two minutes [7]. The most promising capturing technique is using an aero-dynamically controlled capturing device (ACCD), showing the best performance and lowest risk [7, 8].

DLR is currently preparing for flight testing the "in-air-capturing"-method on a laboratory scale by using two fully autonomous test vehicles. Preliminary results are already available and are published in [15].

3 DATA ANALYSES

Various launch configurations, all of them based on reusable first stages without solid strap-on boosters, have been investigated by DLR-SART. The common mission assumptions are listed in section 2.1.

More detailed information on the systematic design analyses of VTL-lift-off-landing mode with either RTLS or DRL return mode is provided in [3]. Similar design analyses of different VTHL-lift-off-landing mode are described in [17]. Providing a technical description of all these concepts is reaching far beyond the scope of this paper. **The legends in the following graphs indicate a hydrogen stage with the capital letter H and a methane-stage with the capital letter C while following numbers specify the approximate propellant loading in metric tons.**

Beyond these more generic RLV-types with various separation Mach-numbers and propellant combinations, also characteristic data of two intensively studied DLR RLV-launcher concepts are included when appropriate: The already briefly described ASTRA LFBB concept

[12] (see Figure 6) representing the LFBB return mode and the SpaceLiner TSTO satellite launcher. The latter is a derivative of the ultra-fast passenger transport designed for delivery of heavy payloads into GTO and other orbits. The satellite launch configuration as shown in Figure 9 is described in more detail in [20, 21]. As an important difference to all other concepts presented here the SpaceLiner has a parallel arrangement of two winged reusable stages influencing the optimum flight trajectory.

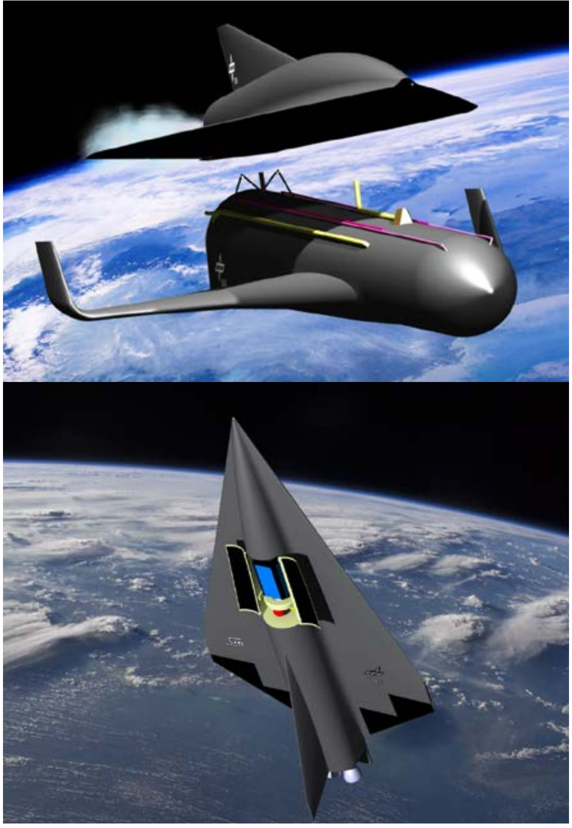

Figure 9: Artists impressions of stage separation (top) and of satellite payload release from SpaceLiner 7 Orbiter's open payload bay (bottom)

The SpaceLiner Booster (SLB) stage which is based on the IAC return mode is mainly of interest in this paper.

3.1 Ascent flight

The first important question addresses, how the landing and return modes of the RLV-stages are affecting the launcher ascent profiles. Figure 10 shows for different selected launchers altitude vs. velocity up to RLV MECO. The design separation speeds reach from 2 km/s up to 3.8 km/s (approximately Mach 6 to 13) representing the range of interest for future European RLV.

As all configurations have vertical lift-off and a similar mission, the differences are relatively small in the beginning but tracks diverge afterwards. The RTLS configurations have the steepest flight profile, minimizing the huge amount of their return fuel as is explained in more detail in [3].

The most striking difference is found for the SpaceLiner Booster with a significantly shallower flight path. The explanation is not in the booster itself but in the winged reusable second stage with internal cargo bay (compare Figure 9) which can make use of the atmospheric lift forces at high altitudes without risking to damage the payload. For most of the other RLV landing and return modes no characteristic deviations can be detected in the axes arrangement of Figure 10 because the RLV and also the second stages' T/W are more vividly driving the optimum ascent profile.

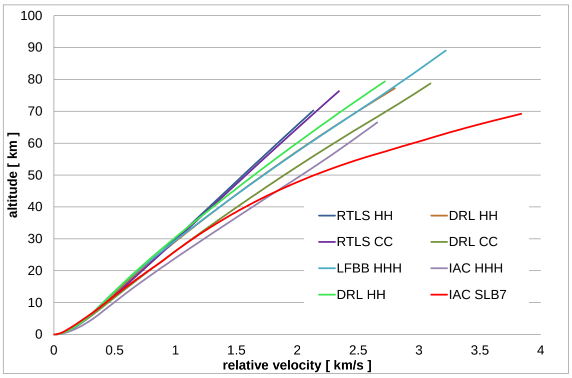

Figure 10: Ascent profile of selected RLV-configurations up to 1st stage MECO

During the ascent flight of launchers significant performance losses occur because the rocket engines do not only accelerate the vehicle but also have to act against Earth gravity and aerodynamic drag. These losses are depending on the flight profile as well as the aerodynamic configuration of the launch vehicle. The trajectory optimization process has the task of minimizing the total losses while respecting the technical and safety constraints. Detailed analyses of the different RLVs' data show relatively strong scattering because the influence of the flight and return modes is weak and the impact of T/W is mostly dominant.

The clearest tendencies can be observed when the performance losses are displayed relative to the RLV stage MECO velocity as presented in Figure 11. Gravity losses could reach up to more than 50% of the RLV separation speed while drag losses remain below 10%. The tendency of dwindling *relative* losses with increasing separation velocity is visible. This behavior is to be expected because the flight path angle γ of vertical lift-off launchers decreases with flight time and hence relative gravity losses. As the vehicle climbs out of the atmosphere also relative drag losses decrease. Aerodynamic drag of winged VTHL-stages during ascent is larger than the drag of the VTL-type resulting in 2- to 3-times higher relative drag losses (Figure 11), however, still at relatively low level.

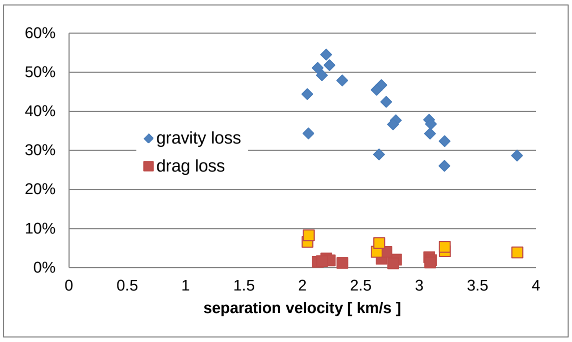

Figure 11: Relative performance losses of RLV-configurations up to 1st stage MECO (orange squares representing winged configurations)

In summary, the RLV ascent flight performance losses are more dependent on the particular configuration with its T/W-ratio than on the landing and return modes.

3.2 Descent or reentry flight

After stage separation and its MECO a reusable first stage is, depending on its return mode, for a certain time in ballistic flight almost outside of the atmosphere. While used ELV-stages are then breaking up in the denser atmospheric layers, an RLV has to safely reenter and sufficiently decelerate in a controlled way that the stage is not crashing on ground. These trajectories calculated in 3- or 4-DOF simulations, plotted in the form of altitude vs. velocity, show characteristic behavior depending on the return modes as visible in Figure 12 and Figure 13. The considerable number of stage types might be confusing at a first look. However, a color coding helps in distinguishing between the different return modes. Orange and brown tones represent the RLV with LFBB mode, light blue the IAC mode and all shades of green the different stages' return in DRL-mode. Three configurations show strikingly different behavior at the extreme ends. The two stages performing RTLS mode (dark blue and purple) almost immediately ignite their rocket engines for a "boost-back"-burn before ascending to relatively high apogees. The SpaceLiner booster (red color) in its shallow profile (compare ascent in Figure 10!) is able to achieve a gentle reentry at relatively high altitude supported by its large wing.

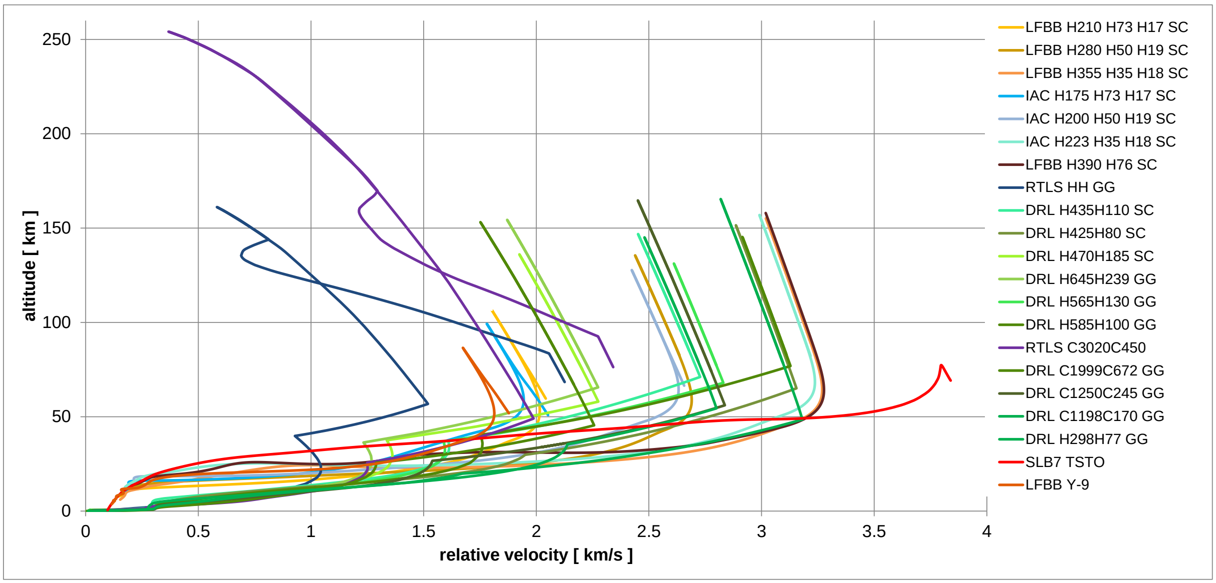

Figure 12: Descent profiles of 1st stage RLV-configurations after MECO

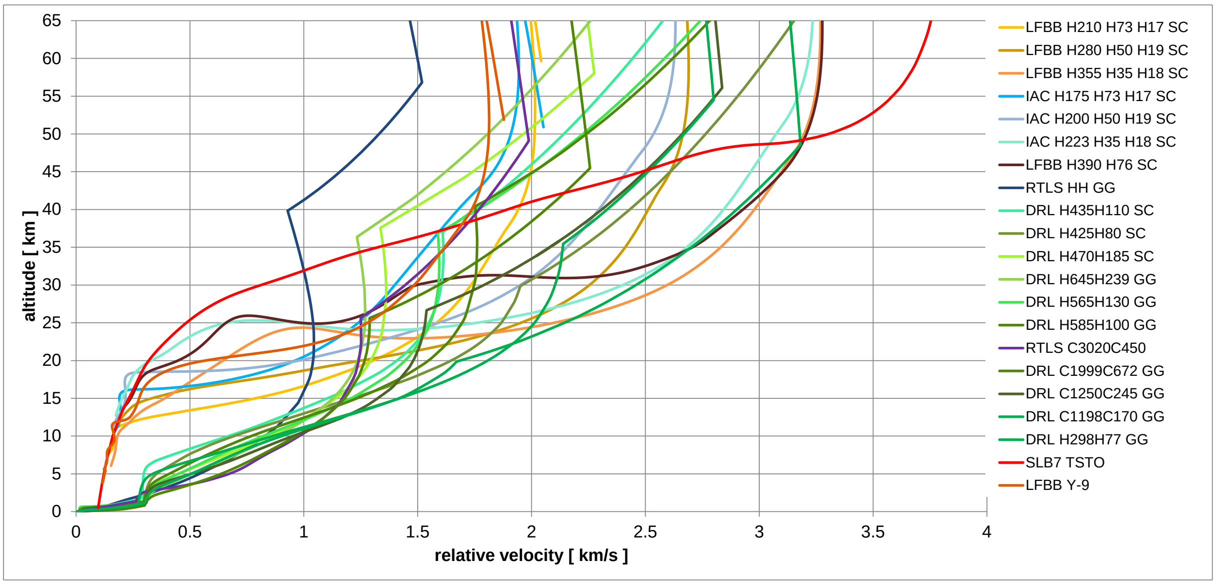

Figure 13: Descent profiles of 1st stage RLV-configurations zoomed into lower 65 km altitude

The other winged LFBB- and IAC-mode RLV are showing more or less similar trajectories but these are significantly different to the SLB7's. This observation can be explained by the steeper flight path of the former during ascent and at the same time the lower wing loading of the SLB. All the winged LFBB and IAC types avoid the dangerous high-speed region at low altitude by utilizing aerodynamic lift-forces without operation of any main propulsion system. Attitude control by RCS-thrusters might be necessary to keep the vehicles at the right orientation in case this cannot be achieved by aerodynamic devices.

On the other hand, the DRL-mode VTL-type RLVs are not capable of generating sufficient lift in similar atmospheric entry conditions. In order not to experience excessive loads, the DRL-stages actively decelerate by using the propulsive forces of the main engines. The ignition of the motors is clearly visible by a sharp bend in altitudes between 50 km and 65 km (Figure 13). Depending on the MECO velocity, the stage velocity is to be reduced between 1.5 and 2 km/s requiring a non-negligible amount of propellant. The RTLS-mode vehicles need a similar (second) deceleration burn performed at almost similar altitudes as for the DRL-types. All VTL-types need a final, relatively short propulsive landing maneuver which is visible in the lower left corner of Figure 13.

The characteristic differences of the reentry flight have a direct impact on the RLV-load histories. During the ascent flight the stresses on the launcher are very similar to those of conventional ELV. Therefore, the reentry mechanical and thermal loads could have an influence on the stage's dimensioning and hence mass. Any excessive heatflux or pressure and vibration might damage the RLV, demanding additional maintenance and refurbishment challenging the economic interest of an RLV.

The same color coding for the RLV-types as above has been used again for the load histories. The normalized acceleration loads in x- and z-direction are presented as a function of flight time after MECO in Figure 14. Winged (LFBB, IAC) and non-winged (RTLS, DRL) are almost perfectly separated in the positive and negative zones of the algebraic sign. Actually, the difference is due to the opposite orientation of the stages during reentry and does not result in a principally different structural load. The acceleration caused by the main rocket engines is defined to act in positive x-direction. With the aft-facing reentry of RTLS and DRL the axial load factor could reach up to +9 g when engines are fired for propulsive deceleration. The nose-facing reentry of the LFBB- and IAC-types could decelerate up to -3g. Note further, the characteristic shapes of progressively increasing propulsive loads compared to the more sine-like aerodynamic forces (Figure 14 top).

In the applied stage coordinate system of these investigations, the normal load factor n_z puts the LFBB- IAC- and also RTLS-RLV on the positive side of the axis while DRL is found on the negative position. Such sign conventions do not mean anything for the almost rotational symmetric non-winged VTL-types. Almost all n_z-loads remain within 4 g absolute values with the only notable exception the Methane-powered RTLS-stage approaching a peak of almost 8 g.

The winged stages as investigated in [17] all reduce the AoA in an aerodynamically closed-loop control to keep n_z within 4 g as shown at the bottom of Figure 14. This has been simulated in 4DOF considering also pitching inertia and calculation of necessary flap deflection to achieve an aerodynamically trimmed state. After passing their load maxima all winged stages are approaching n_z of 1 g when reaching a balanced gliding flight. All non-winged types are close to n_x of 1 g at the end of the simulation because of the vertical touchdown of the VTL-stages at this point.

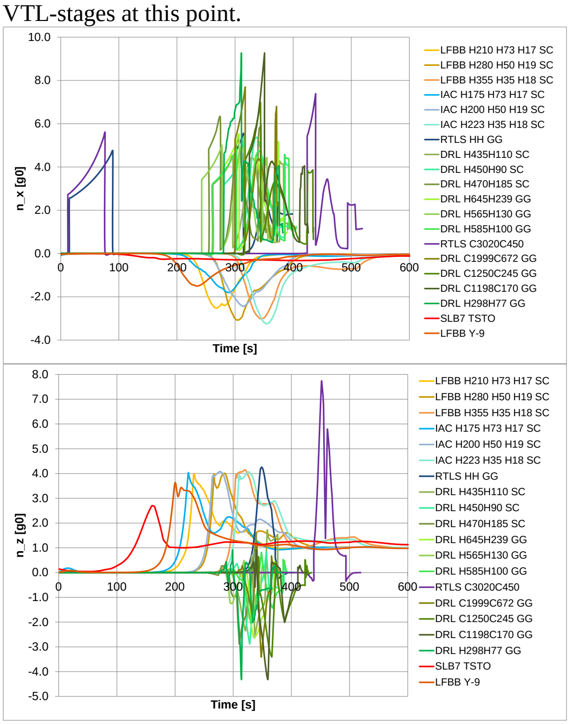

Figure 14: Acceleration loads of 1st stage RLV-configurations, time after MECO (top: n_x, bottom n_z)

Mechanical loads on the structure are furthermore generated by the dynamic pressure for which the reentry histories of the different configuration types are presented in Figure 15. The peak q-data as have been found show dramatic differences with the non-winged DRL- and RTLS types reaching up to 200 kPa while the SpaceLiner Booster with large wing is remaining below 1/30th of this value.

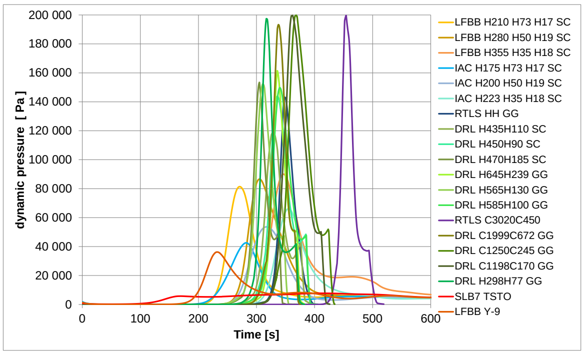

Figure 15: Dynamic pressure of 1st stage RLV-configurations, time after MECO

Dynamic pressures beyond 50 to 100 kPa are unusual for aerospace vehicles and such high loads could cause significant structural penalties. Therefore, before tolerating such high values which considerably exceed those during the ascent flight, a more detailed analysis is required. Figure 16 shows the axial forces and bending moments along the example launcher configuration of DRL-type with LOX-LH2-propulsion for different load cases.

The red dashed line represents the maximum product $q \cdot \alpha$ during ascent flight while the purple dashed line the $q \cdot \alpha$ in descent flight, the red solid curve the axial force during ascent and the blue solid line the axial force generated by the deceleration burn. As can be seen from Figure 16, the dimensioning loads for the RLV's primary structure are acting during ascent conditions. This remarkable result is explained by the longer configuration during ascent which additionally is carrying the relatively heavy upper stage and payload. The DRL-stage is in this example design case not penalized by the high dynamic pressure peak of 200 kPa. However, such a high-q flight profile requires the AoA to be controlled within tight boundaries in all reentry conditions. If such a requirement is actually feasible in a robust practical design is to be assessed in more detail in the future.

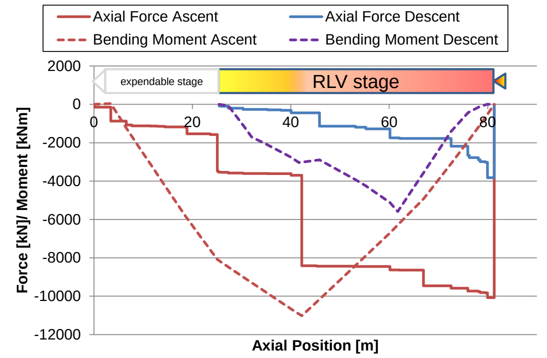

Figure 16: Forces and bending moments acting on 1st stage DRL-configuration in ascent and descent load cases

All types of atmospheric reentry vehicles are subject to aerothermal loads. The heat flux history has a principally similar behavior as the dynamic pressure, reaching its maximum slightly before q_{max}. In Figure 17 the estimated stagnation point heatflux of the winged RLV of LFBB- and IAC-type are plotted. Values are calculated with an empirically derived formula based on the assumption of 0.5 m nose radius which is a good approximation of the individually different geometry. Smaller radii (e.g. at wing leading edges) would see higher heatfluxes if subjected to the freeflow conditions. The RTLS- and DRL-type vehicles enter the atmosphere with their engine bay in forward position, directly facing the hypersonic flow. This geometry at stagnation point is much more complicated which excludes the usage of simple heatflux estimation formulae. For this reason all RTLS- and DRL-vehicles are removed from Figure 17. Reference 3 shows for one DRL-example CFD-results of the thermal conditions during reentry and retro-boost.

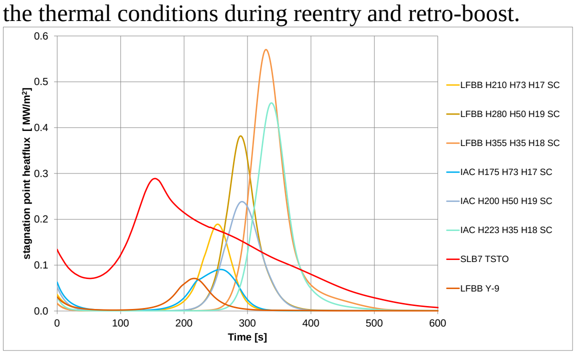

Figure 17: Stagnation point heat flux of winged 1st stage RLV-configurations, time after MECO

As a rule of thumb for atmospheric reentry vehicles it can be stated: the faster the reentry-speed, the higher the heatflux on the vehicle. The plots in Figure 17 demonstrate that the rule applies if the aerodynamic configuration is similar like the LFBB- and IAC-types of [17] but is no longer accurate if one compares the peak heat flux of the SpaceLiner Booster (290 kW/m^2) with those of the LFBB-type H355 (570 kW/m^2) which is almost twice as high although its separation speed is significantly lower.

Note, despite the reduced peak flux of the SLB7 its integral heat load is larger reflecting the higher energy state. Lower heat peaks could be beneficial because they may avoid expensive, high-temperature resistant materials and the lifetime of TPS and structure can be increased.

The explanation of this seemingly paradox behavior is related to the shallow SLB7TSTO-trajectory supported by low wing loading and a low ballistic coefficient ($m/(c_D\ A_{ref})$) and heat load conditions, these coefficients are both for the LFBB- and IAC-types from [17] between 5 and 8 times larger than those of the SLB7. The result demonstrates that even similar reentry and return modes show different behavior depending on the stage's aerodynamic design and wing size.

3.3 Return flight

The DRL- and IAC-return modes require the additional infrastructure of either a sea-going platform or a capturing aircraft. In these modes the stage's return (flight) itself is not affecting the RLV performance which is obviously a major advantage. However, not only additional infrastructure costs but also the question of availability due to local weather conditions could become an issue. The latter is mostly relevant for the DRL-mode and all successful down-range landings of the Falcon 9 have been yet accomplished at low sea swell. At the moment it is hard to quantify the effect of return infrastructure availability. Such important points for evaluation of the different modes are to be addressed in the future but are not yet part of this paper.

The powered return flight modes RTLS and LFBB, while independent of additional infrastructure besides the landing facilities, significantly influence the launch vehicles performance. In the RTLS mode propellant is spent after MECO not only for fly-back but also for the stage deceleration and for a soft landing. The fuel consumption can be divided onto 3 independent engine burns: 1. the "tossback", 2. the reentry deceleration, and 3. the deceleration for soft landing [3]. The first "tossback"-burn is relevant for the return flight propellant as the reusable stage follows after engine cut-off already a ballistic trajectory which would lead it falling into the sea close to the landing site. Thus, this amount of fuel is a reasonable choice for the comparison with the fly-back propellant used by the secondary propulsion system of the LFBB-mode, which itself is started after reentry of the winged stage in subsonic flight conditions.

In Figure 18 the actual propellant mass needed for the return flight as obtained from optimized trajectory simulations is presented. The RTLS-mode dominates the picture with 150 tons of LOX and LH2 or close to 400 tons of LOX and LCH4 required to bring the stages back. It appears in Figure 18 as if the LFBB-mode hardly needs any propellant for the fly-back. This impression is simply result of the scaling effect.

Actually, this amount is progressively increasing with staging velocity due to increasing RLV-stage size and in parallel growing distance to the launch site. However, the range in fly-back fuel goes from only 2.8 tons LH2 for a single ASTRA LFBB with separation below 2 km/s up to 16.7 tons LH2 for an RLV-stage with separation at 3.2 km/s. The return fuel required in the LFBB-mode is more than 18 times better (lower) than in RTLS-mode.

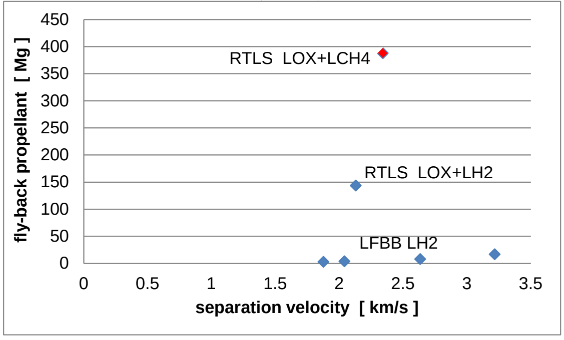

Figure 18: Fly-back propellant mass depending on RLV-stage separation velocity

Beyond the absolute masses of fly-back propellants, it is instructive to look into these masses normalized by the vehicles' total mass. Figure 19 presents two options: the figure at the top shows the values divided by the RLV-stages' mass immediately before ignition of the fly-back propulsion system. In case of the RTLS this happens shortly after separation while for the LFBB the turbo-engines are started after reentry and potentially the residual LOX dumped. Up to more than 50% of the separation mass is to be spent for fly-back propellants in case of RTLS. In the bottom of Figure 19 the fuel is normalized by the launcher's GLOW. While the LFBB-mode's fuel remains below 4% of lift-off mass even in case of relatively high separation conditions, the two RTLS-mode examples require approximately 10% of GLOW only for the stages' "tossback" which obviously downgrades the system's overall performance significantly.

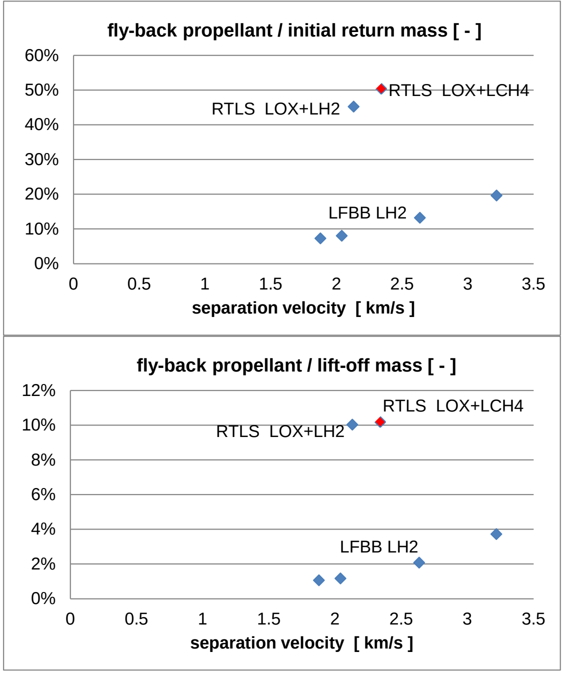

Figure 19: Fly-back propellant mass ratios depending on RLV-stage separation velocity

Without question, comparing simply the amount of fly-back propellant is insufficient for a meaningful assessment of the RTLS- and LFBB-modes. Additional equipment necessary for fly-back is strongly limited for an RTLS-stage because the ascent propulsion system and likely the tanks are reused for the return flight. An LFBB-type, on the other hand, requires a separate airbreathing turbofan including intake and nozzle and, potentially, additional feedline- and tank hardware. The mass impact of this equipment reaches even beyond because the additional components need to be attached and integrated into the RLV-stage. An additional small dry-mass increase is to be expected which is not easy to differentiate from the rest of stage mass. Therefore, such a dry mass comparison of merely fly-back hardware has been set aside and the actual performance impact of this mass is included in the data presented in the following section.

3.4 Performance impact assessment

Any RLV-mode is degrading the launcher's performance compared to ELV due to additional stage inert mass. A comparison of the different performances is of strong interest because these are related to stage size and hence cost. As a reliable and sufficiently precise estimation of RLV costs is almost impossible today, the performance impact comparison gives a first sound indication of how promising the modes are.

The performance impact of an RLV is directly related to its (ascent) inert mass ratio or net-mass fraction, reasonably assuming that the engine Isp is not considerably effected. Inert masses of the stage during ascent flight are its dry mass and its total residual propellants including all those needed for controlled reentry, landing, and potentially fly-back. A specific inert mass ratio is then defined as:

$$\text{inert mass ratio}_i = \frac{m_{i,\text{inert}}}{\text{GLOW}_{\text{stage}}}$$

The higher the inert mass ratio of a stage, the lower is its acceleration performance if propellant type and engine performance are unchanged. Figure 20 presents the inert mass ratios of the stage's dry mass in blue and of its total residual propellants at ascent MECO in yellow. Striking differences in relative distribution depending on the return modes are visible.

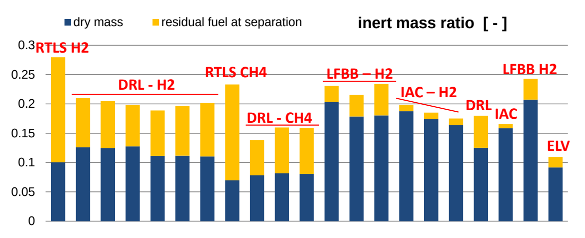

Figure 20: Inert mass ratios of different RLV-return modes

For RTLS-stages the residual fuel is strongly dominating the inert mass with up to 70% of the total. Further, RTLS' inert mass ratios are approximately 30% above all other modes using the same propellant. The "antipodal" mode is in-air-capturing with a small amount of residual propellants left in the tank and a relatively tiny quantity of reentry RCS-fuel bringing dry mass well beyond 90% of inert mass. DRL-mode stages have approximately 50% on fuel and 50% on dry mass while the LFBB-types require an increased amount of fuel compared to IAC-mode but still are clearly dominated by its dry weight inert mass ratio.

However, Figure 20 shows some scattering of data because the size of the stages is not represented in the bar chart. Actually, a larger stage usually has a smaller dry mass ratio. This is due to the behavior of the structural index (SI) which is defined as

$$\mathrm{SI} = \frac{m_{dry}}{m_{prop,stage}}$$

The SI is generally decreasing with increasing stage size due to more efficient design of larger structures and several components do not scale-up with propellant loading and tank mass. Typical examples of SI dependencies for built ELV stages are provided in [3] which also demonstrate the influence of the propellant combination. All the RLV stages in Figure 21 are showing principally similar behavior. The winged stages (LFBB- & IAC-mode) reach higher SI-values as expected because of their additional structure and due to the secondary propulsion system in case of the LFBB. The non-winged DRL- and RTLS-mode stages achieve structural indices close to ELV without major differences due to their return mode. The SpaceLiner booster (SLB7) with IAC-mode is found notably above an expected SI-trend line. The explanation is found in its large-scale wing which enables benign reentry loads (compare data in section 3.2) at the expense of additional mass.

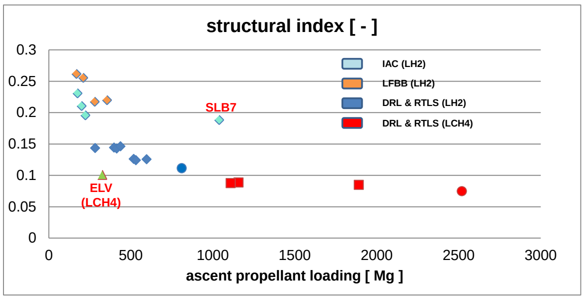

Figure 21: Structural index depending on RLV-return modes and ascent propellant loading

Actually relevant for any performance comparison are the stages' inert mass ratios, as discussed above. The overview in Figure 22 shows remarkable differences in the relative position of the return modes when compared to the SI in Figure 21. RTLS is now found far above all other types while the IAC-stages obviously have a performance advantage not only to the LFBB (as already claimed in the past, see [6 - 8]) but also in comparison to the DRL-mode. However, any final judgement on this result requires second iteration design loops of these stages which also would allow for more precise quantification of any edge.

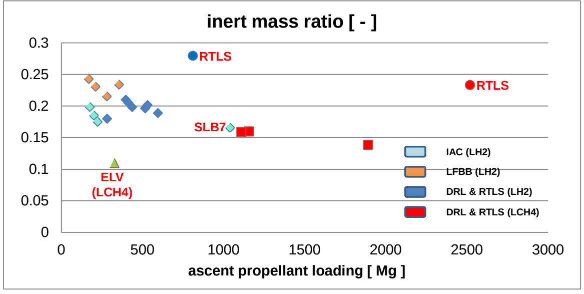

Figure 22: Inert mass ratio depending on RLV-return modes and ascent propellant loading

It is worth noting that the RTLS-mode return flight propellant for the data in Figure 22 does not include any specific margins, while the LFBB-mode return propellants assume an additional contingency between 20% and 30%. It is to be evaluated if a policy without fly-back propellant margin is acceptable for the safe operation of an RTLS-type.

4 CONCLUSION

A systematic assessment of reusable first-stage reentry and return options has been performed for GTO-missions to be launched from Kourou's CSG. Vertical and horizontal landing as well as the different return options autonomous rocket-powered return flight (RTLS), autonomous airbreathing-powered return flight (LFBB), down-range landing (DRL) and so-called "in-air-capturing" (IAC) have been considered. Propellants include hydrogen as well as hydro-carbons both in combination with LOX. The range of separation Mach numbers spans between 6 and 13.

The impact of the different RLV-types on the ascent flight profile is found small and, similar to the ELV ascent flight performance losses, these are more dependent on the particular configuration with its T/W-ratio than on the landing and return modes.

In the descent and atmospheric reentry phase the diverse RLV-types show a notably different behavior between powered and aerodynamic deceleration. These differences have a direct impact on the mechanical and thermal loads acting on the reusable stages with potential effect on the components' lifetime and cost.

Further, the choice of reentry and landing mode as well as the return mode influences the launch vehicle's performance. Winged configurations save significant amounts of fuel but are linked to increased structural weight and additional complexity. The benefit of winged RLV-vehicles is stronger, the higher the separation speed and the more demanding the mission. The launch from Kourou to GTO, as assumed in this paper as reference, is better served by stages with aerodynamically supported lift in reentry when looking from a performance perspective.

Rocket powered return to the launch site (RTLS) of a reusable TSTO-first stage, although marginally feasible, is unattractive in the GTO-mission. The innovative "in-air-capturing" shows best performance and is found almost independent in its lift-off weight of MECO Mach-number. An interesting alternative to the down-range landing (DRL) as in operation with SpaceX and studied here could be a VTL-stage with small wings for aerodynamic deceleration during reentry but vertical landing. Such a configuration, currently under investigation at DLR as an improved SpaceLiner booster ("SLB8"), might allow for an improved inert mass ratio.

A reliable quantified cost assessment of the most promising RLV-launcher configuration requires a relatively detailed iterated stage design. DLR-SART research on this subject will continue to allow sound foundations in any future European launcher decision.

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