IAC-25-D2.3.2

Technical Characteristics of Future In-Space-Transportation Infrastructures

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In this paper, orbital transfer vehicle (OTV) concepts will first be described in a tour-d'horizon by their performance, key design and technology features (propulsion type, propellants, other available key data…) and their mission portfolio considering past and contemporary ideas or realized hardware. A specific focus is on applications relevant for European space activities.

The paper continues with the description of preliminary technical modeling of such transfer stages. The OTV characteristics are selected to be compatible with partially reusable heavy-lift launch vehicles previously investigated by DLR. The required technology readiness level is based on an intended operational maturity of the transfer stages within the next 25 years.

Keywords: OTV, space tug, RLV, Space Shuttle, SpaceLiner

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
GEO	Geostationary Earth Orbit
GLOW	Gross Lift-Off Mass
GTO	Geostationary Transfer Orbit
ISS	International Space Station
LCH4	Liquid Methane
LEO	Low Earth Orbit
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cut Off
MR	mixture ratio
OTV	Orbital Transfer Vehicle
RCS	Reaction Control System
RLV	Reusable Launch Vehicle
RTLS	Return To Launch Site
SLB	SpaceLiner Booster stage
SLME	SpaceLiner Main Engine
SLO	SpaceLiner Orbiter stage
SLP	SpaceLiner Passenger stage
STS	Space Transportation System
TDRSS	Tracking-/Data Relay Satellite System
TRL	Technology Readiness Level
TSTO	Two-Stage-To-Orbit
TVC	Thrust Vector Control

1 INTRODUCTION

Large space infrastructures as well as deep space missions are under preparation worldwide and could also require in Europe significantly more performant space transportation systems in the foreseeable future compared to what is existing today. Some promising technical options exist and DLR has investigated a potential roadmap [1]. Such launcher concepts, likely reusable in one or two stages, aim for transportation from Earth to LEO.

The introduction of reusable upper stages raises questions about the future of in-space operations and infrastructure, as these stages must return to Earth – optimally from low Earth orbit (LEO). While such stages can theoretically access other orbits, the associated fuel costs and performance penalties make them less competitive than expendable upper stages.

As a result, reusable upper stages are typically optimized for LEO missions, which limits overall mission flexibility. Although expendable kick stages can restore some flexibility, they run counter to the principle of full reusability. In contrast, orbital transfer vehicles (OTVs) that remain in space and perform transfers to higher or inclined orbits could provide a compelling solution.

In addition, small satellite launchers often rely on kick stages as well to cover the so-called "last mile", that is transporting the payload or multiple payloads from the insertion orbit to the destination orbit(s) with high precision.

Several reusable launcher operators, complemented by operators in the small launcher segment, have already identified OTVs as critical for enabling access to more demanding orbits, such as GTO/GEO, or for deploying satellite constellations with precision.

Additionally, the private sector increasingly proposes in-orbit services such as:

- Payload recovery or end-of-life management for satellites,
- Payload hosting,
- Re-boosting of satellites or space stations,
- Refueling of orbital assets.

This paper will provide an overview of major past and present projects via literature research, propose a classification scheme. It also presents an analysis of the collected data in order to identify tendencies within the identified concepts with respect to selected classification categories.

1.1 Context

In recent years, orbital transfer vehicles have attracted increasing attention across the launch industry, in the United States and other space-faring nations, including Europe.

Multiple orbital destinations including exploration ambitions to the Moon or interplanetary require additional transfer stages. ESA is starting to define and evaluate a "hub and spoke" space logistics network to reach the final orbits (e.g. constellations phasing, exploration missions…) and provide transportation support for in-orbit servicing (see e.g. [2, 3]).

The purpose of ESA's "InSPoC is to facilitate and enable a dedicated ecosystem of in-space transportation for Europe, which will enable complex missions, establish a sustainable orbital economy and, crucially, keep European industry at the forefront of technological advancements in this field. InSPoC, part of ESA's future space transportation programme FLPP, is rapidly building a network of European industrial partners, de-risking innovation and facilitating rapid technological advances through collaboration, financial and technical support." [3]

According to ESA "Europe is already at the forefront of the development of […] OTV technology" [3]. The organization's "aim is to develop the interfaces required to move to the next level, creating an intermodal transport system in space with docking and refilling capabilities, shared intelligence systems and advanced logistics configurations." [3]

2 CLASSIFICATION OF ORBITAL TRANSFER VEHICLES

2.1 Definition

DLR has classified OTVs along pre-defined categories in a literature survey [4]. An OTV is defined to discriminate it from other constructs operating in space as follows:

- an OTV is an autonomous space vehicle with the purpose to transport items or humans from one point in space to another or to provide pre-defined functionalities to another object operating in space and
- it accomplishes one or more distinct missions each within a limited time frame.
- It is not part of a space transportation system with the purpose to achieve orbital velocities.

As such, an OTV is *not*:

- a space station that is a space-based infrastructure providing its core functionality (housing astronauts) either permanently or for at least several months while staying in one specific orbit,
- an upper stage of a launch system and as such an OTV does not allow an otherwise suborbital system to achieve orbital velocities.

This definition of OTV applies hence to kick stages as well although these vehicles often are an integral part to space launch systems as long as these kick stages are not indispensable to achieve orbital velocities. It shall be noted that occasionally launch operators highlight their kick stage both as orbital velocity delivery system and orbital transfer vehicle. As such, there is a certain grey zone with respect to the kick stage classifying as an OTV.

2.2 Categories

Nine categories for key characteristics have been set up in [4] that help differentiating and categorizing OTVs. Figure 1 shows these categories.

The individual characteristic categories can be explained as follows [4]:

- **Mission**: This category is related to the target of one mission. An insertion into an Earth orbit, be it by altitude or inclination change or else performed by an OTV is considered an Earth-bound mission. Lunar-bound missions include transport missions from Earth to the Moon but also missions that are purely performed within the vicinity of the Moon. Interplanetary missions would aim at trajectories going beyond the Earth-Moon system.
- **Function**: This is the task to be performed by the OTV which is not directly but maybe indirectly linked to the target. These functions could be to change the altitude of the orbit or its inclination, to transport cargo between one point to an orbital facility (e.g. space station), retrieving waste from an orbital facility, payload hosting (providing certain functionalities to payloads, e.g. attitude control during staying in an orbit, de-orbiting of satellites having reached their end-of-life state etc.
- **Objectives**: Some OTV concepts are sent on a mission that only have one specific purpose, e.g. offering last-mile coverage to one payload. Others may be used during one mission to insert several payloads in different orbits or to ferry supply to a space station on the arrival leg and taking back waste during the departure leg.
- **Operation** scheme: Two different operation schemes are distinguished. One is *ground-based* which means that the OTV will be launched by a launch system every time it has to execute a mission, whereas *space-based* concepts stay, once launched, in space and perform their missions from there. Contrary to ground-based OTV concepts space-based concepts will have to be designed for quite long residing times irrespective of the fact if they are used in a ground-based mode from time to time.
- **Payload class**: (Multiple payloads are summed up and treated as one single payload mass irrespective of the deployment scheme etc.).
    - Micro: less than or equal to 100 kg
    - Small: 101 kg to 500 kg
    - Medium: 501 kg to 1000 kg
    - Heavy: 1001 kg to 5000 kg
    - Very heavy: 5001 kg to 10000 kg
    - Super heavy: above 10000 kg

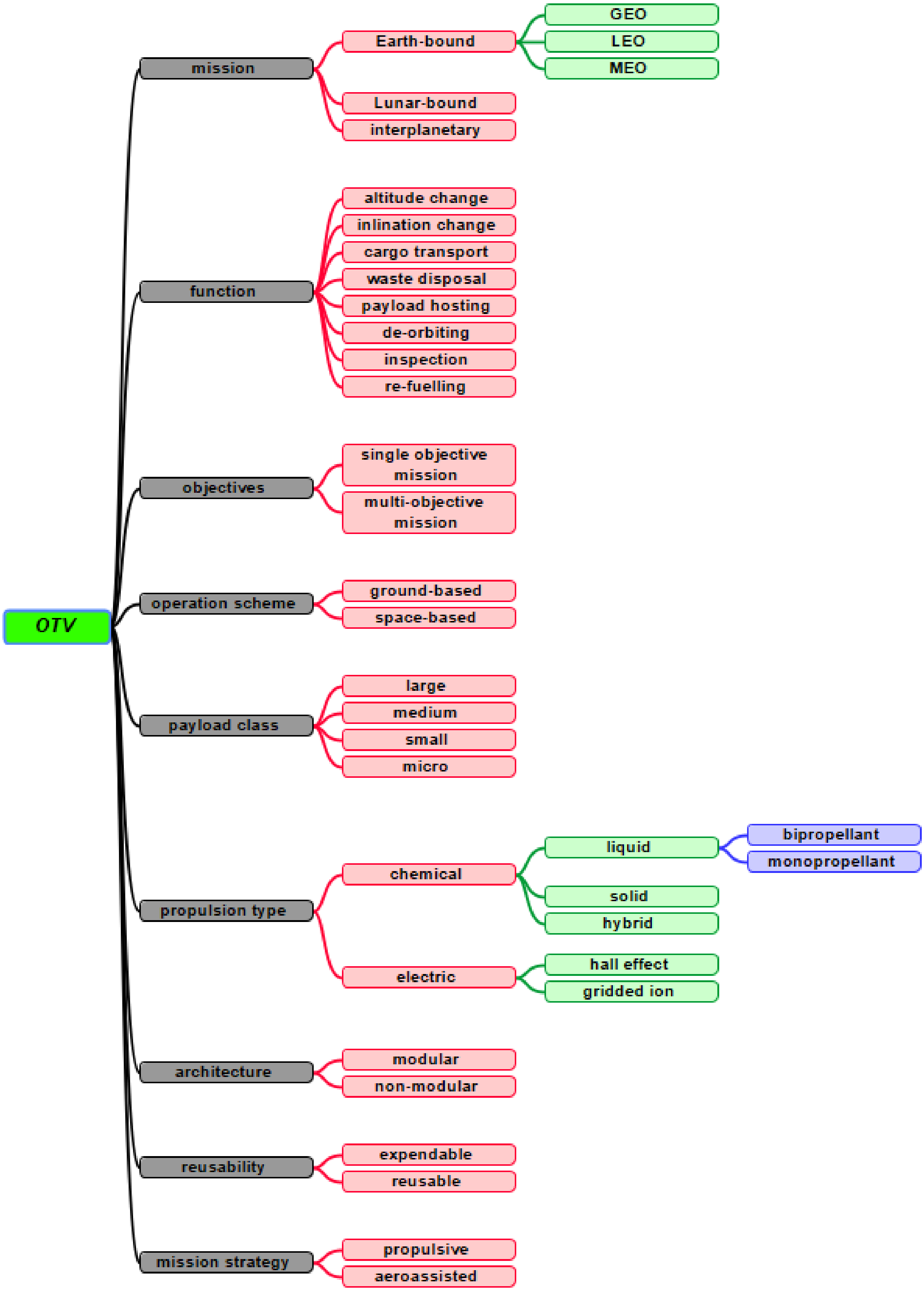

Figure 1: Characteristic categories for OTV classification [4]

- **Propulsion type**: Propulsion for orbital applications can at first be classified in two major categories: chemical and electric. While the former uses energy generated by a chemical reaction or decomposition to energize gas for thrust generation, the latter uses electromagnetic processes. Within each of these two propulsion types, several solutions exist, each with their own advantages and drawbacks. Depending on the mission needs and design requirements, one type of propulsion may be better suited than the other. The choice of propulsion type will have a considerable impact on the final architecture of the vehicle and is generally one of the first design choices made during a development. Applicable considerations extend to the duration of orbital residence time, thrust requirements, number of engine re-ignitions, attitude and position precision, fuel consumption, fuel stability and management, impact on architecture and mass, etc.
- **Architecture**: In this context being understood whether the design is modular or not. Modular with respect to OTV architecture means that the vehicle's composition itself can be adapted to the mission needs, e. g. by mounting additional components, even small propulsive modules to the OTV.
- **Reusability**: Reusable OTV can be uses several times accomplishing several distinct missions before their end-of-life. These may be OTV that stay in orbit for longer periods awaiting new missions to be performed or OTV recovered and re-launched after each mission. OTV releasing several spacecrafts in different orbits during one single mission are not counted as reusable.
- **Mission strategy**: two types are distinguished: one that solely relies on propulsive force for its maneuvers and one that uses, in addition, aerodynamic forces for deceleration, the latter being termed "aero-assisted". This term applies to OTV that may use aerodynamic forces from time to time, but not necessarily exclusively. This classification is made since the capability to use aerodynamic forces for maneuvers has a strong impact on the OTV architecture that tends to carry a drag- or lift-generating surface. The principal interest of so called AOTV is well recognized since decades with an early example of a systematic analysis published in [5]. An implementation of the aerodynamic force supported mission strategy has been delayed to date due to serious technical challenges.

3 CONCEPTS, PROJECTS AND REALIZED ORBITAL TRANSFER VEHICLES

Recently, DLR has compiled a data collection of different proposed and realized OTV in the last 50 years. [4] The following three subsections provide an overview and partial extension or update of this literature review.

3.1 Historic transfer stages

The first wave of OTV or space tugs came with the event of the partially reusable Space Shuttle (STS) in the US and potentially with the Soviet Energia Buran. These heavy reusable upper stages were designed to reach merely LEO and, thus, required transfer stages to serve other, higher energy orbits required by many commercial and scientific missions.

One of the earliest proposals for an orbital transfer vehicle was innately related to the Space Shuttle program. This OTV concept simply named "Space Tug" was developed in the early 70's, see [6] and meant to expand the launch capabilities of the Space Shuttle to geosynchronous orbits. It was designed to be operated in a ground-based mode and meant to be reusable with a total life time of 20 missions. The Space Tug was designed to stay six days in orbit minimum and to have a total payload of at least 3000 pounds (1360.8 kg) for a transfer from a 100 nautical mile (185.2 km) orbit at inclination of 28.5° to a geosynchronous orbit. Its propulsion system was to be based on LOX/LH2.
The 80's and 90's were marked by many further OTV studies that were to expand Space Shuttle capabilities or those of other US-based launch systems. The Payload Assist Modul or (PAM) was among these concepts. While the PAM A, developed by McDonnell-Douglas [7, 8] did not go beyond concept phase, its successor PAM-DII [7, 8] was operational between 1980 and 1985 whereas PAM-D [8, 9] was retired as late as 2009. All PAM models were propelled by a solid propulsion system and as such not destined to be reusable but ground-based. The PAM-A concept was planned to be capable to lift a 2000 kg payload, the payload capability of the PAM-D was about 1260 kg and up to 1880 kg for the PAM-DII [10]. Figure 2 shows the PAM-D leaving the Space Shuttle payload bay while carrying the SBS-3 satellite.

Figure 2: PAM-D with SBS-3 satellite being deployed from Space Shuttle Columbia during STS-5 mission, [11]

The Inertial Upper Stage (IUS) was developed by Boeing and its primary use was to serve interplanetary or other institutional missions such as TDRSS satellite delivery to GEO [7]. Noteworthy missions were the launch of the Magellan probe to Venus, the Galileo mission to Jupiter and Ulysses to the polar region of the Sun using a PAM-S (S for special) as a kick motor or the Chandra X-ray Observatory. It was finally retired from operations in 2004 and was principally capable to deliver a 2270 kg payload to GEO. As the PAM models, it was propelled by a solid motor. It was ground-based and used on the Titan-4 rocket and the Space Shuttle [12].

Another realized OTV concept was the Transfer Orbit Stage (TOS) resulting from a cooperation between Martin-Marietta Corporation and the Orbital Science Corporation [7, 13]. It performed its first flight on 25 September 1992 atop a Titan-4 rocket to launch the Mars Observer Probe and was only used another time almost a year later on 12 September 1993 on the Space Shuttle to deliver the Advanced Communication Test Satellite (ACTS) [14]. According to [13], it was planned to have a payload capability of 6097 kg, but if it did have this performance capability, it never came close to use it during its two flights. As the other OTV mentioned above, it relied on a solid propulsion system and was operated exclusively in a ground-based mode.

Aerojet Technical Systems Company developed the concept for the High Performance Propulsion Module (HPPM) [7] for the Space Shuttle and "(…) sized to roughly twice the PAM-D performance" (p. 135 [7]). It was to be propelled by the storable N_2O_4/MMH TRANSTAR 1 engine. Aerojet developed a further concept for a Space Shuttle upper stage named Liquid Propulsion Module (LPM) [7], with a GEO performance of 1540 kg using the same engine as the HPPM.

Neither the Centaur-G nor the Centaur-G Prime [7, 16] ever reached operational status as a powerful cryogenic OTV for the Space Shuttle although having reached significant maturity during development [16]. It was a derivate of the high-performance cryogenic upper stage Centaur in its various subvariants that flew atop of different versions of the Atlas and Titan launch system. The Centaur-G and G Prime were to be propelled by two LOX/LH2 RL10-3-3A engines and meant to provide GEO respectively interplanetary capabilities to the Space Shuttle. The Centaur G was cancelled after the Challenger accident due to safety considerations of the manned system and overall re-orientation of the Space Shuttle operations. This decision was a major drawback for the overall space transportation capabilities of the STS.

The Apogee and Maneuver Stage (AMS) [7] was planned as an upper stage for the Space Shuttle, and could optionally be used in conjunction with the TOS. It was a concept developed by Orbital Science Corporation and have a payload capability to GEO of 2548 kg [13] but was never realized.

NASA's Orbital Maneuvering Vehicle [9, 15] did not go past project phase either. Its function went far beyond the habitual capability enhancements for the Space Shuttle. Apart from payload delivery or multiple payload insertion or transfer to GEO, it was meant to perform servicing tasks such as re-boosting or de-orbiting of satellites, or providing services to large observatories or unmanned platforms launched from the ISS including their retrieval for maintenance purposes. According [9] it was designed to be used "(…) as a reusable remotely controlled, free flying space tug" (p. 327f).

In 1980, the preliminary design of a NASA concept of a space-based OTV was presented in [17]. It was designed to ferry payloads up to 50 metric tons from LEO to GEO and was planned to be propelled by four cryogenic 89 kN engines. In addition, it should have had a lifetime of 50 missions before being refurbished. Its gross lift-off mass was to be 182 metric tons. This mass is even above the maximum payload mass ever transported into LEO orbit to this date requiring a multi-mission assembly/fueling up.

European companies provided their visions for orbital transfer vehicles in the 1980s as well. MBB and Aerospatiale proposed the Orbit Transfer and Servicing Vehicle (OTSV) [18] offering transportation, servicing and repair functionalities for then envisaged European COLUMBUS Polar Platform (PF) or the COLUMBUS Free Flying Pressurized Module (FFPM). According to [18], the OTSV should operate between the COLUMBUS-PF or -FFPM and a US-American crewed space station which in the 1990s evolved into the ISS. Envisaged transport tasks included the transport of crew members between both space assets and a recovery of the OTSV by the Space Shuttle or the HERMES vehicle for some of the scenarios. Ariane 5 or the Space Shuttle would place the OTSV into its orbit.

Another European proposal, the Automatic Servicer, was presented by the French space agency CNES [19]. This orbital transfer vehicle was to perform in-orbit inspections, visual assistance for satellite deployment and handling operations for telecommunication satellites. It would carry containers with spare modules in a weight range of 50 to 200 kg. Its propulsion was planned to be based on LOX/LH2 and should operate in GEO.

In [20] Matra Espace presented the Teleoperated Service Vehicle (TSV) that should be capable to place spacecraft in their orbits, retrieve and to provide servicing to spacecrafts and offer logistic support for space stations. Several mission scenarios were envisaged, involving space-based transfers between a spacecraft and a space station, from a launch vehicle to a space station. Another mission scenario was a ground-based transfer to an orbit with launch by Ariane 5 or the Space Shuttle and a recovery by the Space Shuttle.

The Automated Transfer Vehicle (ATV) [21] was condensed out of the previous studies and became a major European contribution to the International Space Station (Figure 3). Its primary task was to resupply the ISS and dispose of waste. It was launched five times atop the Ariane 5 G rocket, with a payload up to 7700 kg. It performed one round trip before being disposed upon atmospheric reentry. Its last flight was on 29th July 2014.

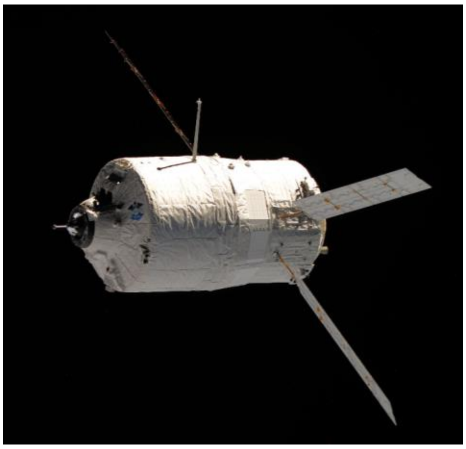

Figure 3: Automated Transfer Vehicle [22]

3.2 Operational space stations resupply vehicles

The longtime workhorse for space stations resupply (Salyut, Mir, ISS) is the Progress spacecraft, that has delivered goods to various space stations since the late 1970's, alongside its crewed version Soyuz [50]. Progress has a payload capability of roughly 2200 to 2600 kg depending on the variant. It has a 30 day in-space autonomy capability and is, in addition to resupplying the space station, the task to re-boost the ISS.

The Dragon capsule from SpaceX [26] also supplied the International Space Station, while its successor Dragon 2 [27] can also transport crew members to and from the ISS. It is propelled by 16 hypergolic Draco thrusters whereas their launch escape system is propelled by eight SuperDraco engines running on hypergolic liquid propellant as well.

In 2013, Orbital Science Corporation has put the Cygnus capsule into operations that performs supply and orbit lifting tasks to the benefit of the ISS [30]. It can be flown atop of either the Antares, the Atlas V or the Falcon 9 rocket.

The Japanese counterpart to the ATV the unmanned H-II Transfer Vehicle (HTV) or Kounotori (Japanese for "white storch") was an unmanned resupply vehicle to the ISS, [56]. It was first launched in 2009 on an H-IIB rocket and performed its final mission to the ISS in May 2020. A successor, the HTV-

X may enter into service yet this year. Similar as the ATV, the HTV was used as a waste disposal carrier as well.

The Chinese Tianzhou [51] assumes the corresponding tasks to the Chinese Tiangong space station. It was first launched in 2017 on Long March 7 and offers about 7400 kg cargo capability in its improved version.

3.3 Current new activities

In the wake of the emerging landscape of new small launchers and the push for reusable launch systems, new OTV concepts are proposed. This section attempts to give an overview of contemporary concepts that may still be under development or which already performed flights. A considerable rise in OTV (and Orbital Maneuvering Vehicles OMV) is observed after 2020, cumulating for now in a launch of 18 commercial vehicles in 2023, see [24] (Figure 10.8, p. 291). Considering the very dynamic and sometimes volatile environment of startups proposing complementary services as the bigger companies well established since a long time this overview does not pretend to be exhaustive let alone complete.

Many of these concepts fall into the category "kick stage" enlarging the mission spectrum for the actual launch system.

ArianeGroup is currently developing the ASTRIS kick stage [25]. It is planned to perform spacecraft delivery from GTO to GEO, on trajectories for exploration missions and multi-orbit delivery for constellations. Dimensions of a planned derivative are 4.1 m diameter and 1.95 m height with engine nozzle and payload assembly fitting (PAF). The dry mass reaches 890 kg, plus PAF mass of 74 kg and loaded propellant mass is 5200 kg. Space storable RP-1 or Ethanol are planned as fuel with HTP as oxidizer. [57]

Blue Ring is a versatile OTV concept by Blue Origin [28] intent to perform in space logistic tasks and delivery, such as refueling, serve as data relay etc. Its first test flight was on January 16, 2025 with the inaugural launch of New Glenn [29]. The transfer platform is to carry more than 3000 kg, is refuelable and should be capable of serving as a refueling depot [30]. Blue Moon is a proposed Moon transfer and landing vehicle of the same company using LOX-LH2 with a cargo capacity of 20 tons in a landing & return scenario [57].

The Centaur V serves as the cryogenic upper stage of ULA's Vulcan launcher. Currently the stage can operate for 12 hours in orbit and the goal is set to last for days in the future [30].

Firefly Aerospace, who successfully developed its Alpha rocket (payload class of about 1 metric ton into LEO), currently develops three variants for their Elytra OTV [32]:

- Elytra Dawn: target orbit LEO, single mission, payload stacks up to 1000 kg,
- Elytra Dark: target orbits cis-lunar and beyond, persistent in orbit, payload stacks up to 16 metric tons, and
- Elytra Dusk: transfer from LEO to GEO, payload stacks up to 16 metric tons.

Rocket Factory Augsburg (RFA) proposes the Redshift OTV for their RFA One launcher. According to company information [33] this OTV shall be used to position orbital spacecraft or other in-orbit services like altitude, phase or inclination changes. They announce further functionalities like payload hosting, satellite inspection, space debris removal, end of life management or life extension services. It shall have a modular architecture and serve a wide range of orbits, including SSO, MEO, GTO, GEO and Lunar Transfer Orbits (LTO) with a payload capability ranging from 150 kg into GEO to 1300 kg into a 500 km SSO.

Colibri is the proposed kick-stage or OTV (called in-space transportation vehicle, ISTV) of the small Maia-launcher under development in France. Its diameter is announced at 3 m with a height of 1 m and 400 kg dry weight [57].

Rocket Lab has flown its Photon spacecraft, [34]. It is used to deliver payloads to their respective orbit once launched. According to [35] it has a launch mass of 50 kg and has been launched successfully several times since its first flight in August 2020, three times atop the company's own launcher Electron, once atop a Falcon 9.

Some companies offer orbital transfer or servicing vehicles as a stand-alone product. One example is Exotrail (see Figure 4) that has already put its SpaceVan [36] into operations with a first satellite release on March 6, 2024 [37]. They propose "last mile delivery" (e.g. from GTO to GEO), payload hosting and plan to provide payload inspection services as well. It can be fitted to a Falcon 9 [38] but is also planned to be launched atop an Ariane 6 rocket [39].

Figure 4: Exotrail's SpaceVan, artist's impression [40]

Northrop-Grumman's Mission Extension Vehicle 1 (MEV-1) [41] was launched successfully in 2019 as a space-based OTV successfully repositioning Intelsat-901 on its geosynchronous orbit, being a world's first in autonomously docking with a spacecraft. In April 2025, MEV-1 detached from the satellite after having placed it in a graveyard orbit. The succeeding MEV-2 was launched in August 2020 by an Ariane 5 docking with Intelsat 10-02 on April 12, 2021.

Momentus Space offers "(…) in-space infrastructure services (…)" [42] such as transporting satellites and providing payload hosting services. Its Vigoride performed its first demonstration flight in May 2022 and its first commercial mission in April 2023 [43]. According to [43] Vigoride has a payload capability of 750 kg into LEO.

D-Orbit launched its ION Satellite Carrier [44] on top of a Falcon 9 in December 2023. It provides deployment and hosting services for CubeSats up to a mass of 160 kg according to the company.

Mira is an OTV proposed by Impulse Space [45]. It performed its first flight in November 2023 releasing a CubeSat in a LEO orbit [46]. It shall serve orbits ranging from LEO, MEO, GEO, to Cislunar and beyond, offering a payload capability up to 300 kg at a Delta-V of 500 m/s. It has a bi-propellant propulsion system running on Nitrous oxide and ethane. According to [47] Mira has a weight of 300 kg itself.

UARX Space proposes OSSIE (Orbit Solutions to Simplify Injection and Exploration) [48]. It is advertised as a facilitator for CubeSats for achieving their final orbit and to provide inclination and altitude change possibilities. In addition, it shall assist in phasing tasks for constellations. Its propulsion runs on Nitrous Oxide/Propylene and it offers a 200 kg payload performance for a 240 m/s velocity increment. UARX has as well initiated development work on LUCAS or Lunar Cargo Service which shall provide cargo services to the Moon with a payload capability up to one metric ton [49]. According to the UARX website dedicated to LUCAS, the development work has completed phase 0 status.

According to ESA [57], to go towards heavy Moon landing (of more than four tons) four main options can be combined:

- Increase launcher performance,
- Leverage In-Orbit Assembly,
- Refilling in lunar orbit before descent,
- Tugging to LLO.

Moon landings with between five- and ten-tons payload mass on lunar surface will likely require cryogenics engines. Tugging and refilling are considered by ESA as key enablers for heavy Moon landing, supporting the future exploration roadmap. [57]

Nyx Earth and Nyx Moon are OTV proposed by *The Exploration Company*. Slightly above 1 t of non-toxic, storable propellants should be carried by these stages [57].

The US X-37B winged military spaceplane has recently been used to explore such aerodynamic capabilities [30].

An essential part of any large and extensively used in-space-transportation infrastructure are propellant depots as depicted in Figure 5. To be placed in LEO and LLO these are considered as key enablers for heavy Moon landing, supporting the ESA Future Exploration roadmap [57].

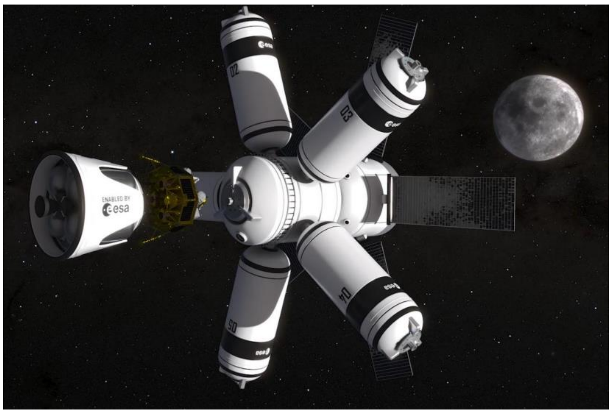

Figure 5: In-orbit refilling of lunar lander on space-tug, in "heavy lunar landing" use-case with Odyssey orbital propellant depot (artist's impression courtesy STS-F) [57]

4 PRELIMINARY TECHNICAL ANALYSES OF TRANSFER-STAGES

Large space infrastructures as well as deep space missions could also require in Europe significantly more performant space transportation in the foreseeable future compared to what is existing today. ESA is starting to define and evaluate a "hub and spoke" space logistics network to reach the final orbits (e.g. constellations phasing, exploration missions…) and provide transportation support for in-orbit servicing (see e.g. [2, 3]).

Together with exploration ambitions to the Moon or interplanetary, this infrastructure will require efficient means of transportation from Earth to LEO. While the ESA-proposed roadmaps are based on Ariane 6 or future derivatives as the reference transportation system to orbit (see e.g. [57]), partially or fully reusable launchers would benefit significantly more from such an orbital infrastructure. Such technical concepts of future European heavy-lift orbital launch capabilities have been investigated by DLR and a development roadmap showing potential key elements was proposed [1]. These launcher concepts form the basis and initial LEO-conditions of DLR's OTV-predesign.

4.1 Reference configurations for Earth to LEO

The investigated RLV-configurations in [1] are assuming similar key mission requirements:

- 250 km x 300 km with an inclination of 25°
- Suborbital option of 30 or 70 km x 250 km, 25° in case of additional kick-stages or powerful space tugs
- Launch site: CSG, Kourou, French Guiana

This reference orbit represents a suitable staging orbit for a translunar trajectory but could also be representative for large LEO-satellite constellations.

The vehicles should be capable of serving secondary missions which were not investigated in the context of the 2024 paper [1]. All upper stages, if expendable after single use, are to be actively deorbited at the end of their mission into Earth orbits to reduce the buildup of additional space debris. A contingency of fuel mass is reserved for this final part of the mission. Potential multi-mission space tugs are considered in the next section.

4.1.1 RLVC-4

Investigations of semi-reusable heavy launchers with the internal project name RLV-C4 [54] have been carried-out by systematic variation of design options on propellant choice or aerodynamic configuration. The RLV-C4 could form Europe's first step to reusable space transportation with a payload performance equivalent or even in excess of an expendable Ariane 6 evolvement as described in [1].

Approaching or even exceeding the payload performance expected for Ariane 6 in GTO or Lunar exploration missions would require extremely tall launcher configurations in case of tandem-staged TSTO with reusable first stage. Therefore, for this class of RLV a parallel stage-arrangement is preferable: a winged stage is connected to an expendable upper segment with potentially various internal architectures. A 14 tons GTO-class with multiple payload capability can be achieved by a 3-stage architecture while still remaining at relatively compact size. [1, 54, 55]

The TSTO-concept with large expendable 2nd stage (Figure 6 at right) was initially defined as an H150, even more compact than the core stage of the classical Ariane 5G. With the heavy-lift LEO mission in mind, the expendable upper stage's propellant loading has been optimized keeping the single SLME untouched. The reusable RLVC-4 stage remains also unchanged.

Figure 6: Launcher architecture sketches of RLVC-4-B configuration as 3STO (left), TSTO (right) [1, 54]

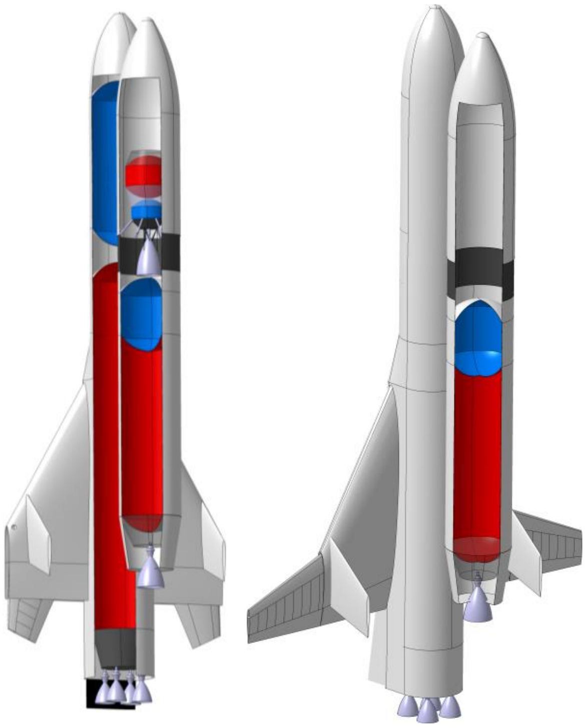

Figure 6: Launcher architecture sketches of RLVC-4-B configuration as 3STO (left), TSTO (right) [1, 54]

A small increase in propellant loading to 160 Mg is delivering the optimum performance with roughly 27900 kg separated payload [1]. The 2nd stage would grow slightly in length compared to what is shown in Figure 6. The disadvantage of bringing this stage into LEO is the requirement of its controlled deorbitation consuming a significant amount of fuel. Therefore, the interest of using a 3STO instead has also been studied for the same mission which allows the large cryogenic stage remaining suborbital and automatically splashing into the Pacific. See [1] and more recent analyses of a large tug stage in the following section.

4.1.2 Heavy-lift configuration RLVC-5

A semi-reusable launcher based on the SpaceLiner 8 booster design and a side-mounted large expendable upper stage has been defined under the designation RLVC-5 (Figure 7). The configuration's architecture is quite similar to the RLVC-4 TSTO (section 4.1.1) but a significantly larger winged RLV-stage with 10 SLME instead of 4. The principal architecture of the expendable stage is even more similar to the RLVC-4 TSTO's second stage with LOX-LH2 stored in a common bulkhead tank and powered by a single SLME in the large expansion ratio variant. Faring and hence stage diameter has been increased to 6.5 m. A huge 24.2 m long fairing that provides 700 m^3 of internal volume is assumed for the super-heavy lift transport with its mass conservatively estimated at 6400 kg.

At lift-off the ten engines on the RLV-booster stage SLB8 are ignited and accelerate to stage separation at high altitudes at the edge of the atmosphere. This maneuver could be relatively relaxed and could allow a certain delay in upper stage ignition if required or beneficial. While the SLB8 is kept in the configuration as described in [52, 53] for its primary application of SpaceLiner, the expendable stage's propellant loading has been varied to find the maximum achievable payload mass.

The investigations reveal that the maximum payload to the reference LEO is found at 80 t with an upper stage ascent propellant of approximately 160 t [1]. Thus, the expendable part of this heavy launcher remains relatively compact in size (length 18.8 m without faring) as visible in Figure 7. Achieving maximum performance, would require some off-loading on the RLV-stage to realize adequate initial acceleration levels [1]. Though this choice is not resulting in the optimum launcher for this particular application, the approach makes sense if the SLB8 designed for the SpaceLiner missions (e.g. [52]) is used for secondary tasks and thus demonstrates its operational robustness.

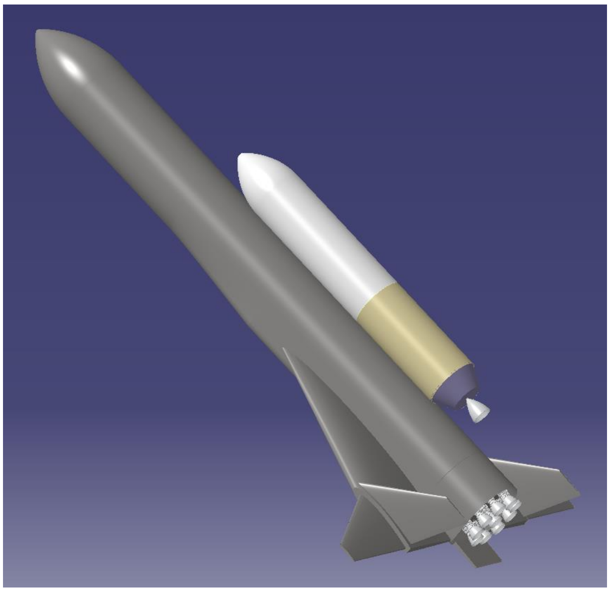

Figure 7: RLVC-5 as CAD geometry

4.1.3 Fully reusable TSTO based on SpaceLiner

The SpaceLiner itself is defined as a fully reusable space transportation system to LEO with payload performance in the A6-class. The parallel arrangement of the two SpaceLiner stages of variant 7, the reusable booster and the orbiter or passenger stage, at lift-off and its main dimensions are presented in reference 52.

The SpaceLiner7 passenger stage's internal design has been adapted for its secondary role as an unmanned satellite launcher. The passenger cabin is not needed for this variant and is instead replaced by a large internal payload bay [52, 53] as shown in Figure 8. Key geometrical constraints and requirements are set that the SpaceLiner 7 passenger stage's outer mold line and aerodynamic configuration including all flaps should be kept unchanged. The internal arrangement of the vehicle could be adapted; however, maximum commonality of internal components (e.g. structure, tanks, gear position, propulsion and feed system) to the passenger version is preferred because of cost reflections.

Further, the payload bay should provide sufficient volume for the accommodation of a large satellite and – if required - its orbital transfer stage. For this purpose, the SLO's propellant loading has been reduced by 24 Mg to 190 Mg compared to SLP with a smaller LOX-tank to allow for a payload bay length of 12.1 m and at least 4.75 m diameter [53, 58]. These dimensions are close to the Space Shuttle (18.3 m x 5.18 m x 3.96 m) and should accommodate even super-heavy GTO satellites of more than 8 m in length and their respective storable upper stage. Large doors open on the upper side to enable easy and fast release of the satellite payload in orbit.

Figure 8: SpaceLiner 7 orbital stage (SLO) in rendering with open cargo bay

Launch of the SpaceLiner 7 TSTO orbital launcher has been simulated from the Kourou space center for various missions. In case of satellites transported to GTO, the injection of SLO occurs into a low 30 km × 250 km transfer orbit allowing the reusable orbiter stage becoming a once-around-Earth-vehicle capable of reaching its own launch site after a single circle around the planet. Subsequently, an orbital transfer is necessary from LEO to GTO using an expendable upper stage with storable propellants. Reference 52 shows the Mach-altitude-profile of the two reusable stages for the GTO-mission ascent.

The SpaceLiner 7 TSTO has also been calculated for the reference LEO-Mission using a bi-boost strategy of the SLO. The initial ascent goes into a 70 km x 300 km LEO before the perigee is to be raised by second SLME burn to 250 km. Reference 1 presents the initial phase of the orbital ascent profile. Almost 20 tons could be delivered if the reusable upper stage itself is circularized. The relatively large dry weight of the SLO makes it attractive even in case of the LEO-mission to consider keeping the orbiter in suborbital conditions and attaching a smaller expendable kick-stage for circularization ($\Delta v \approx$ 66 m/s) to the payload. As a consequence, the achievable payload mass increases to more than 24 tons [1].

4.2 OTV-pre-design for transfers from LEO

A small storable kick-stage or OTV has been defined for raising the orbit from RLV-C4'ssecond stage MECO of 30 km x 250 km to 250 km x 300 km. A separated payload of around 29350 kg could be reached, an improvement of approximately 1445 kg compared to the TSTO [1]. If the final destination of the mission is similar to the reference LEO a fully cryogenic 3STO with H14 3rd stage (as visible in Figure 6 at left) is of limited interest being too heavy and too expensive. However, in case of more demanding missions the picture is changing and such a configuration could become highly attractive for e.g. translunar injection.

For more versatile capabilities, including access to high-energy orbits such as GTO, a larger version of the OTV was already proposed for the SpaceLiner 7 (see previous section 4.1.3 and [58]). Its propellant loading of roughly 17.8 Mg and dry mass of approximately 1.4 Mg are propelled by a hypergolic engine similar to the Aestus engine. The propellant combination N_2O_4/MMH is a potential option. Choosing these propellants enables a relatively simple and robust stage design, which is particularly advantageous for missions requiring multiple re-ignitions and extended residence time in space. However, the toxicity of hydrazine is a serious disadvantage also with respect to regulations as REACH. Currently, the N_2O_4/MMH-combination serves as an example case of the early sizing procedure but does not imply any frozen design.

The large storable stage's tank architecture (Figure 9) is inspired by the EPS and AVUM upper stages leading to a compact layout. The fuel loading is set to 17.25 Mg sufficient to carry a payload mass of 7.9 Mg into GTO and to apply a de-orbit boost at apogee to lower the perigee to altitude nil, considering an Isp of 324 s.

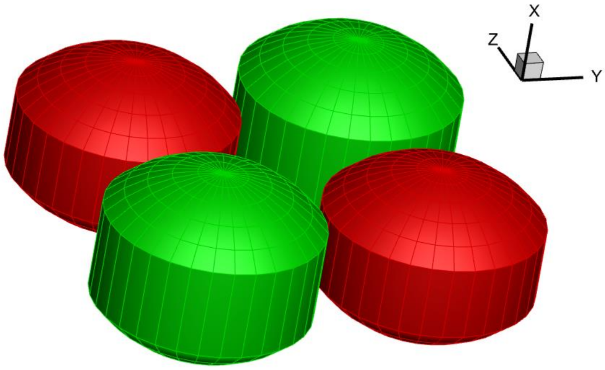

Figure 9: Preliminary OTV-L tank architecture as defined by DLR

An ascent to GEO with a subsequent de-orbiting (lowering of perigee to altitude zero) is not advisable performance-wise, leaving the separated payload mass at disappointing 1.6 Mg. This is a direct consequence of the fuel to be reserved for the high Δv for deorbitation. A graveyard orbit is probably the better option.

The same OTV with fully loaded propellant gives access to an inclination of up to 40° for a 250 km circular LEO to the benefit of a 6 Mg payload with initial reference orbit separation conditions at 25°. Beyond this inclination, a different launch azimuth is at order.

Considering an injection mass of about 26.3 Mg (OTV including satellite payload) into a 30 km x 250 km, inclination 25° orbit achievable by the SpaceLiner 7 TSTO the performances into other orbits are assessed. Table 1 provides some information of achievable payloads for a given inclination change. When necessary, fuel is unloaded to maximize the performance. The current mission sequence is: inclination change (either at descending or ascending node whichever yields a lower Δv), circularization into a 250 km x 250 km, release of the payload and finally stage deorbitation.

Table 1: Performance of OTV-L for inclination change

	Target inclination				
	10°	40°	60°	80°	90°
Unloading [Mg]	4.5	4.6	0	0	0
Payload [Mg]	11.6	11.7	3.1	~0	Not feasible

For inclination changes to 60° and beyond the injected payload mass drops dramatically due to the available fuel mass while the performance capability of the carrier launcher could offer higher performance provided a larger OTV with higher fuel loading can be mounted.

5 CONCLUSION

Orbital transfer vehicle and in-space transportation infrastructure likely will play an increasingly important role in future space transportation involving partially reusable launcher concepts. In this paper, OTV concepts are first be described in a tour-d'horizon by their performance, key design and technology features and their mission portfolio considering past and contemporary ideas or realized hardware with specific focus on applications relevant for European space activities.

Past OTV concepts and operational vehicles were intrinsically linked to the Space Shuttle program. With the termination of the Space Shuttle operations, few projects were continued or set up. While ideas for the use of OTV for in-space logistics continued to be discussed, a new surge of interest in OTV can now be observed motivated by the push onto the market by private companies offering small launchers and by new RLV projects. Both need the capabilities of OTVs respectively kick-stages to increase mission versatility for their launch systems.

The paper continues with the description of preliminary technical modeling of such transfer stages. The OTV characteristics are selected to be compatible with partially reusable heavy-lift launch vehicles previously investigated by DLR.

A first rough design for a kick-stage for the SpaceLiner 7 concept is promising to increase mission flexibility and providing low cost and high-performance access to missions beyond the reach of the purely reusable part. More research on the OTV-topic is intended for the near future.

6 ACKNOWLEDGEMENTS

The authors gratefully acknowledge the contributions of Mr. Sven Stappert, Mr. Steffen Callsen and Mr. Tiago Rebelo.

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