The Space Superhighway: Systems Analysis of an In-Space Logistics Delivery Network

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The number of assets in cislunar space is anticipated to dramatically increase in the coming decades. Many of these newer spacecraft are being designed to take advantage of capabilities currently in development like In-Space Servicing Assembly and Manufacturing (ISAM). Additionally, the National Aeronautics and Space Administration (NASA) intends to develop and maintain a human-lunar presence that will then serve as a steppingstone for human missions to Mars. With continued growth in space operations, the combined demand for payload and propellant delivery in cislunar space could exceed 1,000 t annually within the next decade. In order to meet this projected demand, there is national interest in developing an ISAM-enabled logistics network, commonly referred to as the "Space Superhighway". This study explored several architecture and vehicle-level trade studies in order to better understand what in-space logistics networks may be feasible. The network considered in this study consisted of commercial launch vehicles, resupply tankers, orbital depots, and in-space tugs. This work specifically analyzes high-level trades such as: launch and in-space vehicle propulsion systems, vehicle size, staging orbit, level of vehicle reuse, reuse method, and propellant management strategy. Each of the trades are analyzed across several destination orbits such as Low-Earth Orbit (LEO) and Near-Rectilinear Halo Orbit (NRHO). Propellants and other cargo such as crew logistics, spares, smallsats, and satellite piece parts were considered.

Nomenclature

3DOF	=	3-Degree-of-Freedom
DCH_4	=	Densified Methane
DO_2	=	Densified Oxygen
DRP-1	=	Densified Rocket Propellant 1
ΔV	=	Delta in velocity, change in velocity
EDL	=	Entry, Descent, and Landing
EXAMINE	=	EXploration Architecture Model for the IN-space and Earth-to-orbit modeling
GEO	=	Geostationary Earth Orbit
GTO	=	Geostationary Transfer Orbit
LCH_4	=	Liquid Methane
LH_2	=	Liquid Hydrogen
LO_2	=	Liquid Oxygen
LRP-1	=	Liquid Rocket Propellant 1
LEO	=	Low Earth Orbit
LOX	=	Liquid Oxygen
LV	=	Launch Vehicle
MEL	=	Master Equipment List
NRHO	=	Near-Rectilinear Halo Orbit
PMF	=	Propellant Mass Fraction
ToF	=	Time-of-Flight
TPS	=	Thermal Protection System

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I. Introduction

Small spacecraft (and small pieces of larger spacecraft assembled in space) are ride-sharing on commercial launch services more and more frequently. In the coming years, a network of in-space tugs and propellant depots is anticipated to be available for cargo delivery to numerous orbits. This in-space shipping network would be a critical component of the overall infrastructure, commonly called the "Space Superhighway" [1]. Historically, space access has only been possible for governments with the means to buy a "moving truck". With the Space Superhighway, access to space could soon be more like shipping packages on Earth. This paradigm shift will be enabled by In-Space Servicing, Assembly, and Manufacturing (ISAM) capabilities. This research is attempting to demystify how these capabilities could be effectively utilized by the National Aeronautics and Space Administration (NASA), other agencies, and industry for space exploration and operations.

Forecasting the Space Superhighway's manifestation from concept to reality is challenging not only due to complexity, but because it is such a fundamental departure from all space operations to date. High-quality models typically have plenty of historical data to rely on. Since available historical data is only partially relevant to ISAM-based space architectures, new systems analysis capabilities are being developed in order to fill this knowledge gap and make quantifiable projections on the benefits of specific in-space logistics network concepts. Various architecture and vehicle-level trade studies are explored principally to:

1) Feed vehicle sizing results into a cost-benefit analysis which is published in a complementary paper [2], and elaborate on the methods behind the results that were fed into said paper.
2) Understand the sensitivities of different parameters and assumptions. For instance, does vehicle size matter? What about low-thrust versus high-thrust tugs, specific impulse, staging orbit altitude, level of vehicle reuse, etc.?
3) Compare their performance relative to a "status quo" architecture: dedicated launches (one per mission) and no logistics network or ISAM capabilities.

Propellant delivery architectures to cislunar space using chemical propulsion tankers have been studied in detail previously [3]. However, a broad evaluation of in-space logistics networks would not be complete without considering numerous payload types besides propellant, multiple cislunar delivery orbits, and electric propulsion as a transportation method. The specific impulse of low-thrust, Solar-Electric Propulsion (SEP) exceeds traditional chemical propulsion by an order of magnitude, making SEP tugs a compelling potential "workhorse" to move cargo between cislunar orbits. In order to quantify the benefit of SEP tugs, however, mission design studies must also be done to capture accurate change in velocity (ΔV) and Time-of-Flight (ToF) estimates.

II. Concept of Operations

The Space Superhighway is conceptualized in Fig. 1. Commercial Launch Vehicles (LV) deliver propellant and payloads to Low Earth Orbit (LEO). These payloads can either enter their own orbit or rendezvous with a LEO depot. An in-space electric propulsion tug could rendezvous with a LEO depot or the freely orbiting payloads, dock, then transport the payloads to their final orbit. This work will focus on transfers from LEO to Geostationary Earth Orbit (GEO) and transfers from LEO or GEO orbits to the Moon, but any destination in Cislunar space is theoretically possible. The Space Superhighway is built off of previous work comparing expendable and reusable in-space refueling tankers being delivered to lunar orbit [3]. This work expands on that study by modeling not only the propellant resupply tankers, but the launch vehicles and cargo resupply vehicles, such as the in-space tugs. The two reference resupply architectures, are reproduced in Fig. 2. The fully expendable architecture represents a traditional delivery approach without any ISAM capabilities, whereas the fully reusable architecture represents an ISAM-enabled logistics network. Each architecture's concept of operations is summarized below:

1) A fully expendable architecture: identical tugs are launched by two-stage fully expendable LVs to LEO. Tugs then use SEP engines to transfer to a customer resupply node and deploy payloads. If sufficient propellant remains and there is additional demand, the tugs could transfer to another resupply node where they could deploy more payloads. From the node, the tugs perform a disposal maneuver. More tugs are then manufactured and launched to keep up with customer demand.
2) A fully reusable architecture: identical tugs are launched to LEO by two-stage reusable LVs, then the tugs depart LEO for the first customer resupply node. Once at the first node, the tugs may deploy payloads, refuel a depot, and or loiter and refuel a customer spacecraft directly with a portion of their onboard propellant. The reusable tugs could transfer to another resupply node for additional payload deployment and refueling services. Next, the tugs could pickup other payloads from the node if necessary, such as lunar/biological samples, and deliver said payloads while returning to LEO for refueling. Another reusable LV launches a tanker to resupply the tugs with

propellant and payloads for the next mission. These reusable LV 2^{nd} stages could loiter and resupply multiple tugs, then use what propellant remains to perform Entry, Descent, and Landing (EDL) for reuse. All tankers are recovered, inspected, repaired if necessary, and flown again until all payloads reach the customer node.

Tankers may be large enough to deploy multiple smaller payloads and refuel many small satellites. Alternatively, customer spacecraft like landers could be large enough to require refueling from multiple tankers. Other examples of a multi-launch resupply missions include telescopes or habitats delivered in multiple modules before being assembled in space. Both ends of this spectrum are under consideration in this study. The second Earth-Moon Lagrange point (L2) Near-Rectilinear Halo Orbit (NRHO) was the assumed customer resupply node for most trades, but this study also examined LEO and GEO customer resupply nodes. NRHO was originally selected because its stability offers low

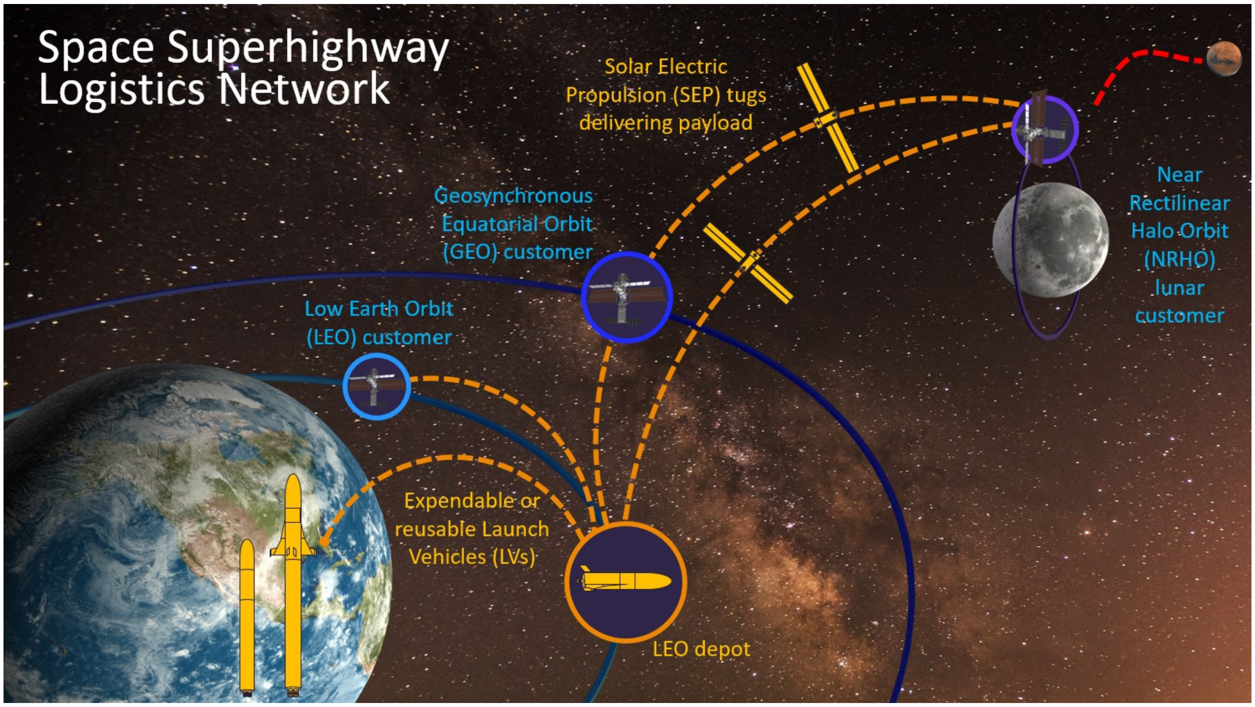


Fig. 1 Space Superhighway Conceptual Architecture (not to scale).

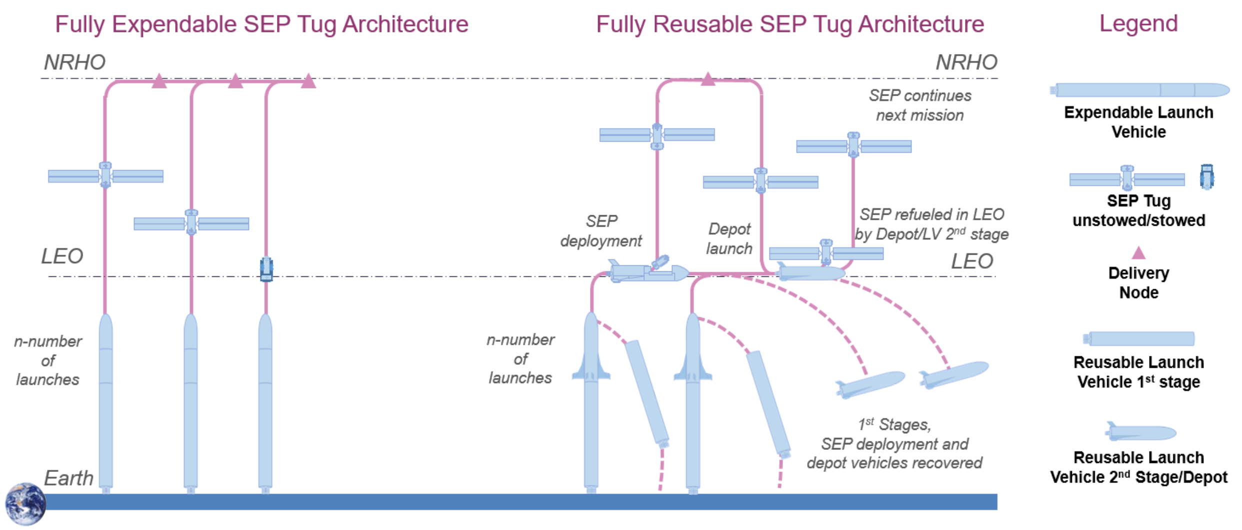


Fig. 2 Fully expendable architecture vs. fully reusable architecture (not to scale).

station keeping, on the order of 1-10 m/s per year [4], and it has a much higher characteristic energy than LEO—offering reusable lunar landers and Mars transit vehicles alike a convenient staging orbit for propellant resupply services [5]. NRHO also has continuous communication coverage of the Earth and Moon and is far enough from these planetary bodies that their heat fluxes do not pose an additional challenge for propellant boil-off mitigation [5]. This study will also build off previous work [3] by considering other payloads besides just propellant. For example: crew logistics, spares, smallsats, and satellite piece parts for in-space assembled assets could be delivered by the Space Superhighway.

III. Tools, Methods, and Assumptions

This section describes the tools, methods and assumptions used in this work. First, the tool Exploration Architecture Model for the IN-space and Earth-to-orbit modeling (EXAMINE) was used to size all the tankers, tugs, and LV stages. Next, the low-thrust mission design was computed analytically using Edelbaum's method for quasi circular orbit transfers. The following subsections provide a detailed description of the tools and major assumptions used in this work.

A. Vehicle & Architecture Modeling

EXAMINE is a parametric tool for sizing in-space and Earth-to-orbit elements [6]. EXAMINE is often used to make high-level architecture trades for pre-phase A systems analysis. The tool offers a rapid way to make relative comparisons between many design options and parametric data to understand trade space sensitivities. Inputs governing assumptions, such as tank material type or propellant type can be changed through a simple user interface or pre-programmed in batches. The user only needs to specify constraints while setting up the model; EXAMINE can converge batches of cases based on those constraints to rapidly generate thousands of unique design points if desired.

In this work, EXAMINE was used to generate a Master Equipment List (MEL) of all subsystems down to each component in each element (space or launch vehicle stage). All subsystem sizing is relative and coupled to the other subsystems. Propulsive events determine propellant mass which dictates tank size. Tank size drives the overall surface area, which impacts the thermal control system size, and so on. The basic mass, consisting of each element's respective subsystems (structures, main propulsion, Reaction Control System (RCS), power, avionics, and thermal control), was used to calculate the predicted mass by adding 15% total margin. EXAMINE uses the predicted and wet mass as well as a list of ΔV events to determine the performance (payload mass) of each architecture design point.

Similar architecture performance estimates and trades could be generated with a much lower-fidelity model than EXAMINE. Component-level mass estimates are not strictly necessary for pre-phase A systems analysis. They are necessary, however, for the cost estimation that this work directly supports (and was submitted as a separate conference paper [2]. This is the main reason EXAMINE was selected for architecture modeling, instead of a lower-fidelity tool.

For the elements in all of the architectures, all subsystems were sized based on subject matter expert-verified models like the avionics, propellant feed systems, and thermal management. A handful of specific noteworthy assumptions made for some of the subsystems is summarized in the following subsections for each respective element type.

1. Launch Vehicles

Usable main propellant mass was the parametric independent variable for sizing all LVs, and payload mass to LEO was the dependent variable, maximized for each LV case. LV sizes varied from medium to super-heavy lift. LV tank outer diameter was scaled in relation to LV stage gross mass (based off historic data like Saturn V and the Shuttle External Tank). As with many existing LVs, all LV stage tanks assumed an insulated common bulkhead for fuel and oxidizer. 1^{st} stages and reusable 2^{nd} stages assumed main propellant tanks were 2195 aluminum alloy and expendable 2^{nd} stages used 304 series stainless steel. These alloys are historically ubiquitous for LVs like the Shuttle External Tank and the Atlas V [7] [8]. O_2/CH_4 and O_2/RP-1 propellants were traded for 1^{st} stages, and O_2/H_2 was assumed for all 2^{nd} stages. Again, similar to existing LVs, the 1^{st} stages have between 9 and 30 pump-fed main engines. 2^{nd} stages have between 1 and 4 vacuum engines, depending on total thrust required (larger stages need more engines). Reusable 2^{nd} stages also have a sea-level engine for the descent and landing burn. Most engine data is historical, but outputs like specific impulse are curve fit in EXAMINE using a NASA tool called Chemical Equilibrium Applications CEA [9].

All reusable stages require landing gear, RCS thrusters, a heat shield, and aerodynamic control surfaces. Reusable stages must also reserve propellant for recovery burns, unlike expendable stages. Reusable stages also have subtanks, which feed into main engines for EDL. Reusable 2^{nd} stages are highly similar to the reusable cislunar tankers modeled in previous work, which can be referenced for further information and illustrations [3]. The only major differences in assumptions in this study and the previous work was the fact that LV stages were sized using EXAMINE, and reusable

2^{nd} stages use new EDL sizing data to predict the Thermal Protection System (TPS) thickness and ΔV for descent and landing. The TPS is based on a Phenolic-Impregnated Carbon Ablator (PICA) mechanically attached to the aluminum structure. Granted, it sounds logical for a rapidly reusable LV stage to also have a reusable TPS (non-ablative). Although a reusable TPS material should be traded in the future, PICA would not necessarily need replacement between every mission, and the process could be significantly automated.

If we define Propellant Mass Fractions (PMF) as:

$$PMF = m_{propellant}/m_{wet}$$

where $m_{propellant}$ and m_{wet} are the stage usable propellant mass and wet mass respectively, one can argue it is more advantageous for LVs to have higher PMFs, since this effectively means a higher ΔV is achievable for a given stage inert mass. Since LVs perform most of the mission ΔV, their performance drives the entire system's performance. Thus, LV PMF is an important parameter to the overall architecture. One way to raise a cryogenic stage's PMF is by subcooling the propellant. This idea is becoming increasingly commonplace in the launch services industry [10]. The impact of subcooling O_2, RP-1, and CH_4 relative to loading propellants at their normal boiling points was explored.

2. Tugs

The SEP tugs were also sized with usable main propellant mass as the parametric independent variable. Solar power generation and usable RCS propellant was also varied, since these parameters impact the tug's payload mass and ToF to the delivery node. Tugs have composite tanks for xenon and RCS propellant. Xenon was selected as the main propellant because of its high performance, but krypton was considered because it is much more affordable. Results on both will be discussed in IV. Tugs included 24 clustered xenon Hall effect thrusters with direct drive power processing units. Numerous publications were used to develop the electric propulsion system model, namely [11–13].

Solar arrays were modeled based on four-junction, space-rated, roll-up blankets with two single-axis tracking booms. 33% was the assumed beginning of life efficiency. In reality, arrays without radiation tolerance would degrade in cislunar space. However no degradation in power generation was considered. Instead, the useful lifetime of the tug was limited to 10 years. Future work could explore the effect of replacing arrays after 10 years instead of launching a new tug. Batteries were modeled to power avionics during eclipse. Other systems requiring power generation, like the EP thrusters, would not be able to operate until the eclipse is over. The power management and distribution model as well as the model capturing the thermal management of said power system came from numerous sources, primarily NASA technical reports [14, 15].

3. Depots

As mentioned in the concept of operations, reusable LV 2^{nd} stages and reusable tugs can loiter in LEO or the customer node, then resupply customers and other elements in the logistics network. This enables the benefits of depots without requiring the development of more unique elements. Since reusable elements already have significant boiloff mitigation and ample RCS systems for long-duration loiter, no major vehicle changes were made for elements that act as depots.

B. Mission Design

The Earth-to-orbit flight performance for LVs is typically analyzed with tools like Program to Optimize Simulated Trajectories [16]. While a detailed 3-Degree-of-Freedom (3DoF) flight performance analysis based on the vehicle sizing data is conducted, conservative assumptions were made based on existing LVs to obtain some preliminary flight performance results that are still as accurate as possible. All 1^{st} and 2^{nd} stages were sized to a 1.4 and 0.4 stage Thrust-to-Weight (T/W) ratio, respectively. 1^{st} stage main engine specific impulse at sea level was also assumed for the entire stage's flight profile. The size of 2^{nd} stages relative to 1^{st} stage wet masses was set based on flight heritage and previous studies, and may need minor adjustment based on the 3DoF flight performance results. A fairly conservative 9.2 km/s total ΔV to reach a 200 km circular LEO has been assumed for now. The ΔV split between each stage was determined by assuming all available propellant can be consumed, and payload was maximized.

The low-thrust portion of the mission ΔV (carried out by the tug) was obtained with an analytical first-order approximation developed by Edelbaum [17]. The initial circular and final quasi-circular orbits assessed were LEO and Lunar-Distant High Earth Orbit (LDHEO). From LDHEO, the tugs then perform more low-thrust burns to reach the NRHO delivery node, rendezvous, and dock with customer spacecraft (reusable tugs also require ΔV to undock and return to LEO). In reality, an eclipse would interrupt thrusting, but thrust was assumed constant since the duration of eclipses is trivial. Since specific impulse is assumed constant throughout the tug's mission, the Tsiolkovsky rocket equation is still valid and can be used to maximize customer payload delivery mass.

IV. Results

Despite having thousands of inputs and links between subsystems, trade studies converged rapidly (a few minutes per case) thanks to EXAMINE's parametric modeling capabilities. Running hundreds of cases enables sensitivities on payload size, engine specific impulse, vehicle outer mold line, and trade studies such as propellant type, propellant storage temperature, vehicle thrust-to-weight ratio, reuse assumptions, tank and structures materials, cryogenic fluid management strategy, staging orbit, etc. Performance measures will include payload delivered per mission, payload delivered per launch, payload delivered per ton of propellant consumed, and payload delivered per year.

A. Low Earth Orbit

This subsection presents the performance and trade results of the LVs sized in EXAMINE to deliver payloads and propellant to LEO. No other elements were assumed necessary for LEO payload delivery. Table 2 summarizes LV main engine performance.

Table 2 LV main engine performance sizing results.

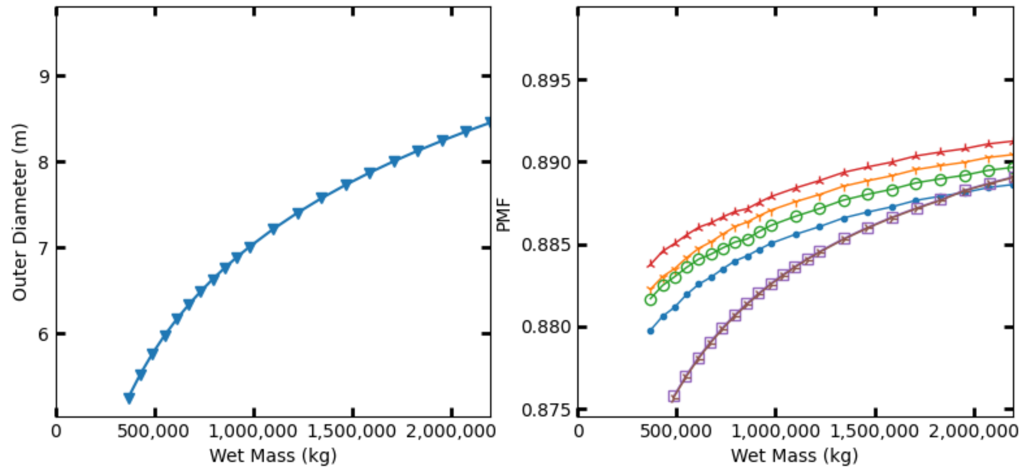
Propellant Type	Specific Impulse (s)
O_2/RP-1	312.9 (Sea level)
O_2/CH_4	323.6 (Sea level)
O_2/H_2	456.0 (Vacuum)

Fig. 3 trades propellant type and loading temperature for fully reusable and fully expendable LVs. Each data point represents a single parametric design case that the vehicle model converged. As shown on the left of Fig. 3a, outer diameter was set to smoothly scale with LV wet mass, unlike the previous study [3]. This allowed trends in results to be easier to recognize. Many observations can be made from the relative differences in these results. As expected, PMF increased as LV wet mass increased in all cases, suggesting larger scale LVs are more efficient. PMFs were slightly lower than anticipated in all cases across the board, suggesting the results are slightly conservative. One possible explanation is that the structures subsystem model is too conservative. Future work will include trading different materials or a different structures model altogether, but the relative trends are more important than absolute results. O_2/RP-1 and O_2/CH_4 1st stages were generally found to have comparable PMF and payload mass for a given design point. However, as shown in 3b, O_2/CH_4 had slightly higher payload delivery than O_2/RP-1, thanks to the higher specific impulse. Keep in mind, all 2nd stages were O_2/H_2.

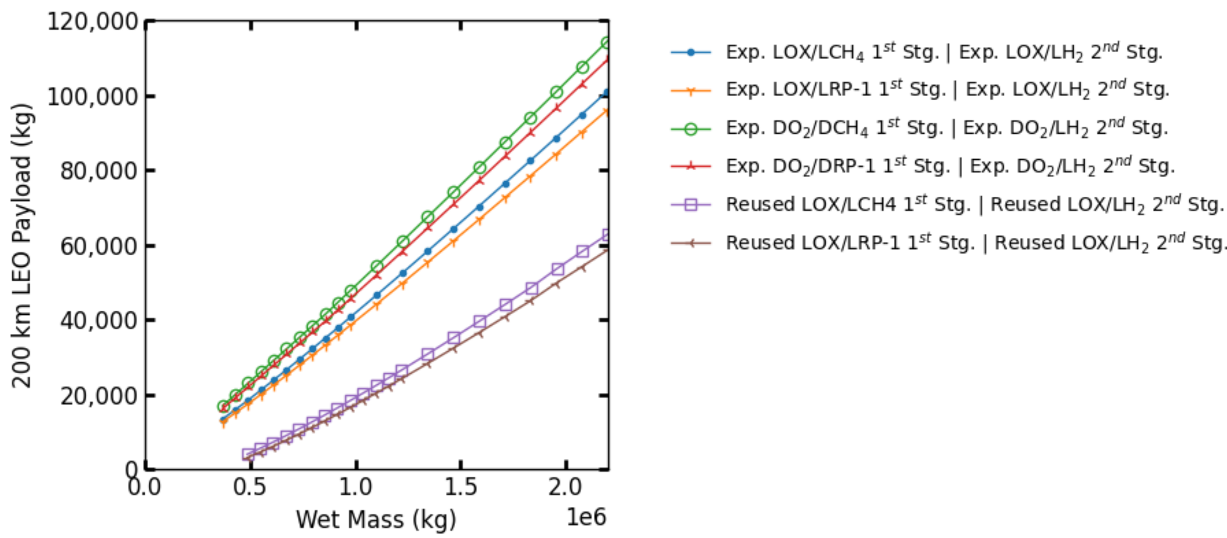
Despite the fact that hydrogen was not subcooled and no slush propellants were considered, subcooling O_2, RP-1, and CH_4 still increased LV performance in all cases. Although the reusable LVs lag in performance, they could potentially make up for this in other areas like total cost.

B. Near-Rectilinear Halo Orbit

The ΔVs obtained using Edelbaum's method for transfer from LEO to LDHEO and LEO to GEO were verified using previous findings, such as the low-thrust data in Table 4 of Merrill, et. al. [18]. The Hall thruster performance predicted by the parametric tug model is summarized in Table 3, including a validation against experimental results produced with a 20-kW Hall thruster fabricated by NASA Glenn Research Center [19]. The parameters in Table 3 are all at 100% throttle setting. The 400 V discharge voltage results were used for consistency with experimental results. The analysis itself assumed 300 V discharge voltage. Since the simulated and experimental Δs are consistent, the model can give a sufficient relative comparison between xenon and krypton. Although xenon has higher thrust for a given discharge power, krypton has higher specific impulse. Thus, xenon tugs should have shorter ToF, but lower payload delivered than krypton. Technically, relative differences in vehicle attributes like PMF also contribute somewhat, but the ΔPMF between the two was consistently below 15%. Given expendable tugs have less overall ΔV than reusable



(a) LV Attributes.



(b) LV Performance to LEO.

Fig. 3 LV parametric sizing.

Table 3 Hall thruster performance sizing results.

				Parametric Model			Experimental Results		
Propellant	Xe	Kr	Δ (%)	Xe	Kr	Δ (%)	Xe	Kr	Δ (%)
Thrust (mN)	1112	841	-24.4	881	751	-14.8	1240	988	-20.1
Specific Impulse (s)	1,759	2,201	25.2	2044	2558	25.1	2470	3090	25.2
Flow Rate (mg/s)	64.5	38.9	-39.6	44.0	29.9	-32.0	51.0	32.6	-36.2
Discharge Power (kW)	20.0	20.0	0	20.0	20.0	0	20.0	20.0	0
Discharge Voltage (V)	300	300	0	400	400	0	400	400	0

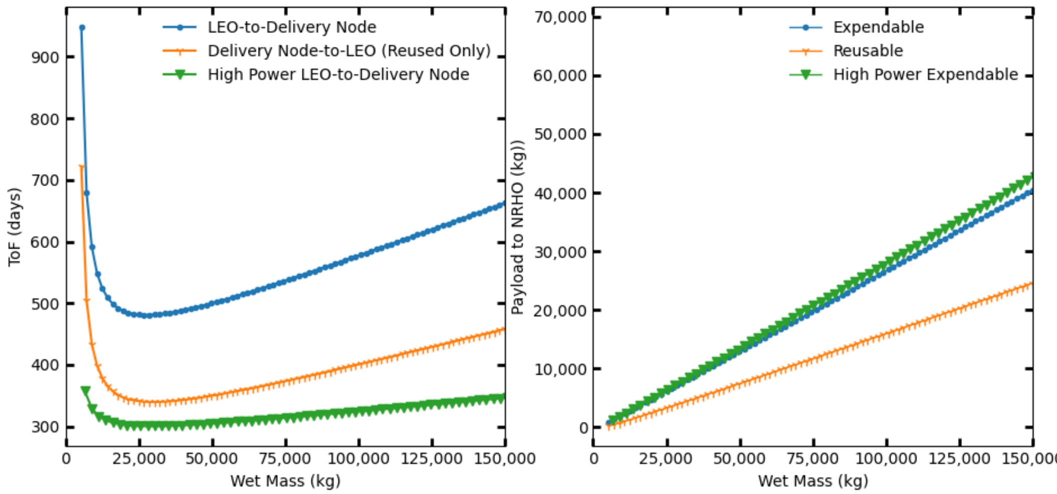


Fig. 4 Tug Performance to NRHO.

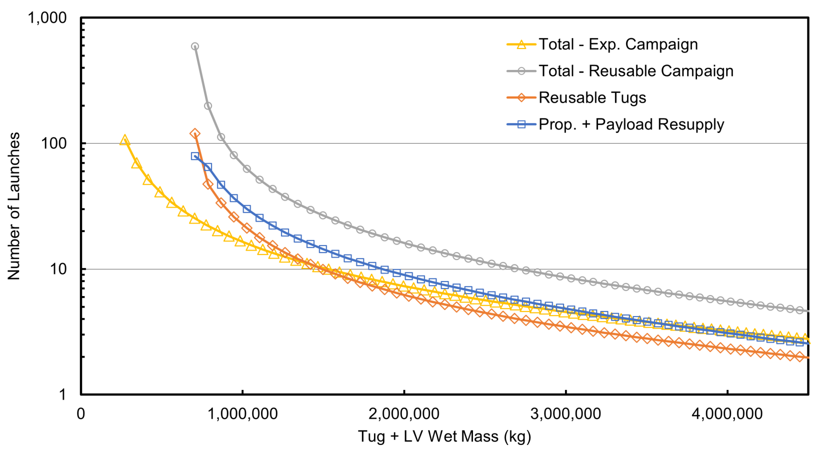


Fig. 5 Full Reuse versus Fully Expendable: 250 t Payload NRHO Delivery Campaign.

tugs, it's no surprise they have higher payload mass delivery, as shown in 4. Despite this fact, and the fact that the ΔV to return from NRHO to LEO is over 7 km/s, the reusable tugs still had appreciable performance thanks to the Hall thruster's high specific impulse. Thus, SEP tugs could be a key to enabling logistics networks beyond LEO.

The baseline tugs had extremely long ToFs for NRHO payload delivery. Assuming their life cycle is 10 years, each tug only completes 2-3 missions total. Thus, sensitivities studies were necessary to identify the driving parameters. The effect of tug power on payload and mission ToF is also shown in 4. Clearly, tugs with higher power yield more reasonable mission ToFs. However, no reusable cases converged with a positive payload mass to NRHO for the higher power levels assumed (not enough propellant was available). This result highlights yet another challenge of NRHO logistics delivery. For closer orbits like GEO for instance, nearly all reusable, high-power tugs could deliver positive payload mass.

1. Logistics Network Campaign Trade Study

The fully expendable and fully reusable NRHO delivery architectures are shown in Fig. 5 for a hypothetical campaign delivering 250 metric tons of generic payload (which could be crew logistics, habitats, landers, satellites, or other cargo). This assumed one tug was deployed per LV, but several could be co-manifested if the LV had enough throw mass and volume. The LVs were all LO_2/RP-1 and LO_2/LH_2 for the 1^{st} and 2^{nd} stage, respectively. It should be unsurprising that expendable architectures always had the fewest number of total launches. What is interesting, is how small the difference was: for the largest vehicle sizes, the full reuse architecture only required 2 more launches than the expendable architecture. If the cost of refurbishing elements is appreciably lower than producing them, one would anticipate these reusable architectures to be more affordable.

Since missions supplying the campaign's cargo can be done in series or parallel, the campaign duration is not definitive. The fully reusable architecture is constrained by the number of LVs available, and how quickly they can be reused (tug ToF is only consequential to campaign duration for the right side of the plot, since each tug can only complete 2-3 missions), whereas the fully expendable architecture is constrained by how quickly the elements can be produced and launched.

One major advantage of cargo delivery with the fully reusable SEP tug over the fully reusable chem tanker is the lack of a need to mitigate boiloff. As explained in the previous study [3], the fully reusable architecture required several LEO propellant topoffs before the chem tanker departed for NRHO. The chem tanker would either need advanced cryofluid management, an aggressive launch cadence (the latter was assumed), or a combination thereof to prevent the chem tanker's propellant from boiling off in LEO during the propellant topoff mission phase. These challenges are circumvented by the SEP tugs since they use storable propellants. Until order-of-magnitude improvements are made in launch cadence or cryofluid management, logistics networks may need to rely on SEP tugs or expendable elements.

V. Conclusions

The goal of this work was to answer the question: "What are some of the most feasible options for an in-space logistics network?" That question is addressed through performance-measure-driven conceptual systems analysis on an architecture, vehicle, and mission design level. Parametric vehicle sizing coupled with high-level mission analysis was leveraged to capture a broad scope of options. This approach was found to be a robust method of capturing major performance drivers while also generating MELs for every design point's cost estimation. Without the rigor and efficiency of subsystem-level parametric tools, it wouldn't be possible to explore trades and sensitivities through thousands of design points with such high fidelity. From the generic performance metrics, feasibility of delivering various payloads was derived. LV reuse strategy was found to have greater performance impact than propellant type and storage temperature. Reusable LVs were still found to have enough performance to justify estimating and comparing reusable LV cost against expendable LVs, which is the focus of the complementary paper [2]. Performance and affordability of current and future Earth-to-orbit systems is important for stakeholders both in LEO and beyond.

Delivery beyond LEO is a unique challenge requiring fine-tuned, complex solutions spanning many different elements. Despite the challenges, SEP tugs were found to have tremendous cargo delivery performance, especially to more distant orbits like NRHO. Reusing tugs was also found to be highly advantageous since the propellant required to return a SEP tug is much lower than that of a chemical propulsion tanker. One disadvantage to reusable tugs, however, is solar array degradation, which is accelerated by the radiation environment in the vicinity of the Van Allen Belts. One possible mitigation to investigate is launching tugs to GTO instead of LEO, which is much further outside Earth's gravity well. This would substantially reduce overall ToF and the solar cell degradation rate. This could also permit tugs to complete more missions in their life cycle, which could reduce production costs for large delivery campaigns. The reusable LVs delivering the tugs could either target GTO directly, or receive a propellant topoff first. The latter would be particularly advantageous if the reusable LVs needed to use impulse burns to return to LEO, as opposed to aerobraking. All of these trades could be investigated in future work.

There are numerous advantages to distributing cargo, like piece parts for Gateway or a deep space telescope, in a logistics network consisting of many delivery missions. Not only could this mitigate risk of failure during transportation, it could make mission extension resupplies and upgrades to legacy hardware more feasible, enable goods produced in space to transfer to their customers (such as ISRU materials from the Moon to NRHO and GEO), allow operators to have more evenly distributed business cycles, and potentially reduce delivery cost. All of this would be enabled by ISAM. Highlighting this information helps mission planners more concretely understand the benefits of ISAM capabilities for their future missions and helps guide agency strategy toward more specific decisions that support the development and use of ISAM and the Space Superhighway.

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