IAC-17-A6.8.5

Economic Benefits of Reusable Launch Vehicles for Space Debris Removal

Matthew P. Richardson[a]*, Dominic W.F. Hardy[b]

[a] *Department of Aeronautics and Astronautics, University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, Japan 113-8656*, matthew.richardson@ac.jaxa.jp
[b] *Nova Systems, 53 Ellenborough Street, Ipswich, Queensland, Australia 4305*, dominic.hardy@novasystems.com
* Corresponding Author

Abstract

An analysis of cost savings which could be realized on active debris removal missions through the use of reusable launch vehicles has been performed. Launch vehicle price estimates were established for three levels of reusable launch vehicle development, based on varying levels of technological development and market competition. An expendable launch vehicle price estimate was also established as a point of comparison. These price estimates were used to form two separate debris removal mission cost estimates, based on previously-proposed debris removal mission concepts. The results of this analysis indicate that reusable launch vehicles could reduce launch prices to levels between 19.6% and 92.8% cheaper than expendable launch vehicles, depending on the level of RLV maturity. It was also determined that a reusable launch vehicle could be used to realize total active debris removal mission cost savings of between 2.8% (for a partially reusable launch vehicle in an uncompetitive market) and 21.7% (for a fully reusable launch vehicle in a competitive market).

Keywords: Reusable Launch Vehicles, Active Debris Removal, Space Economics

Nomenclature

$C_{ADC,R}$ - ADCS RDT&E cost
$C_{ADC,T}$ - ACSS TFU cost
$C_{B,ELV}$ - ELV booster stage cost
$C_{B,RLV}$ - RLV booster stage cost
$C_{CDH,R}$ - C&DH RDT&E cost
$C_{CDH,T}$ - C&DH TFU cost
$C_{EPS,R}$ - EPS RDT&E cost
$C_{EPS,T}$ - EPS TFU cost
$C_{F,ELV}$ - ELV payload faring cost
$C_{F,RLV}$ - RLV payload faring cost
$C_{P,R}$ - Propulsion system RDT&E cost
$C_{P,T}$ - Propulsion system TFU cost
$C_{PL,R}$ - Payload RDT&E cost
$C_{PL,T}$ - Payload TFU cost
C_R - Recurring launch cost
$C_{S,R}$ - Structural system RDT&E cost
$C_{S,T}$ - Structural system TFU cost
C_{SB} - Spacecraft bus cost.
C_{SP} - Total production cost for all spacecraft.
C_{TFU} - TFU spacecraft cost
$C_{TPS,R}$ - TPS RDT&E cost
$C_{TPS,T}$ - TPS TFU cost.
$C_{W,R}$ - RDT&E wrap costs
$C_{W,T}$ - TFU wrap costs
$C_{2,ELV}$ - ELV second stage cost
$C_{2,RLV}$ - RLV second stage cost
DC_{ELV} - ELV launch direct cost
DC_{RLV} - RLV launch direct cost
GM_{ELV} - ELV launch gross margin
GM_{RLV} - RLV launch gross margin
M_{ADC} - ADCS mass
M_{CDH} - C&DH mass
M_{EPS} - EPS mass
M_P - Propulsion system mass
M_S - Structural system mass
M_{SB} - Spacecraft bus dry mass
M_{TPS} - TPS mass
N_B - Number of booster stage reuse flights
N_F - Number of payload faring reuse flights
N_S - Number of spacecraft produced
N_2 - Number of second stage reuse flights
P_{ELV} - ELV launch price
P_{RLV} - RLV launch price
R_B - Booster cost as a percentage of launch cost
S - Learning curve slope

Acronyms/Abbreviations

ADR - Active Debris Removal
ADCS - Attitude Determination and Control System
C&DH - Command & Data Handling
EPS - Electrical Power System
ELV - Expendable Launch Vehicle
FY - Fiscal Year
GSE - Ground Support Equipment
IA&T - Integration, Assembly & Test
LEO - Low Earth Orbit
RDT&E - Research, Development, Test & Evaluation
RLV - Reusable Launch Vehicle
TFU - Theoretical First Unit
TPS - Thermal Protection System
USD - United States Dollars

1. Introduction

1.1 Background

In coming decades, Reusable Launch Vehicles (RLVs) could improve access to space by reducing cost barriers and improving availability of space transportation services [1]. This can be achieved through the amortisation of launch vehicle manufacturing costs over multiple flights, which is impossible, by definition for single-use Expendable Launch Vehicles (ELVs). Such a development would reduce risk and improve viability of current commercial space operations, while also improving the feasibility of proposed new ventures. As a result, missions and business plans which are currently considered impractical from a cost perspective could become feasible [2]. The idea of RLVs reducing space transportation costs and fostering growth in the space economy is not new, with proposals for reusable rocket boosters dating back to the late 1950's [3]. However, the high costs of the world's first partial RLV program, the Space Shuttle (shown in Fig. 1), highlighted the challenges associated with developing a low-cost RLV [4].

Fig. 1. Space Shuttle. Source: [5]

Despite these challenges, development of RLVs has continued in the private sector following the retirement of the shuttle. In March 2017, the SES-10 communications satellite was launched aboard a SpaceX Falcon 9 rocket with a flight-proven booster stage (shown in Fig. 2) which was previously used for an International Space Station cargo resupply mission [7],[8]. The SES-10 launch demonstrated for the first time that RLVs could be commercially viable [9].

Fig. 2. SpaceX Falcon 9 launches SES-10. Source: [6]

With commercial RLV operations now underway, the long-term implications of this technology on both the space transportation industry and the wider space sector should be considered. A common concern associated with RLV economics is the high demand for space transportation and subsequent frequent launch rates required to make RLVs commercially sustainable in the long-term [1], 2]. Opening up new markets and economic opportunities through RLV-enabled low-cost, high-availability space transportation is considered to be crucial to stimulating this required growth [2].

Active Debris Removal (ADR) missions represent an application where RLVs could reduce costs and improve economic feasibility. Even with a high rate of Post Mission Disposal for future space missions, the amount of space debris in Earth orbit is expected to increase due to collisions and fragmentation in coming decades. The commensurate increased risk to all manner of orbital assets poses a significant space environmental hazard to continuing space operations [10]. ADR is now considered to be necessary for managing the orbital debris population to ensure continued access to space in the future [11].

Presently, there are several significant issues associated with the development and operation of ADR missions, including but not limited to technical, legal, political and economic challenges [10]. Lower space transportation costs, enabled by RLVs, could reduce the overall cost of proposed ADR missions, improving their economic feasibility. In turn, increased demand for space transportation from ADR missions could improve the long-term business case for RLVs.

1.2 Objectives

The aim of the study described in this paper is to investigate the level of economic benefit which RLVs could deliver to ADR mission concepts. Space transportation price estimates are established based on extrapolation of current RLV operations. ADR mission cost estimates are established using parametric cost estimating applied to detailed mission architectures established in previous studies. These estimates are used to forecast potential cost reductions ADR missions could achieve through RLVs as a proportion of total mission costs. Other potential impacts of RLVs on the orbital debris problem are also considered in a qualitative analysis.

2. Launch Price Estimates

In this section, estimates for RLV launch prices are established. Several different RLV price estimates are established based on varying level of market and technological maturity. An ELV launch price is also established as a baseline for comparison. All prices are adjusted to Fiscal Year (FY) 2020 United States Dollars (USD) for compatibility with ADR mission cost estimates. As discussed in Section 1.1, historical RLV price estimates have been overly optimistic. However, with recent developments, it is possible to establish more realistic estimates of RLV launch prices based on information from industry.

Both the ELV and RLV launch price estimates in this section are based on the SpaceX Falcon 9 launch vehicle. As the only orbital partial RLV currently used in commercial operations, the Falcon 9 is an ideal basis for RLV price modelling. Furthermore, as demonstrated in Fig. 3, even as an ELV, the Falcon 9 is currently the most cost-effective medium-lift launch vehicle on the global space transportation market [9]. Thus, comparison between ELV and RLV launch prices will be conservative, as opposed to comparing the reusable Falcon 9 RLV to a more expensive ELV.

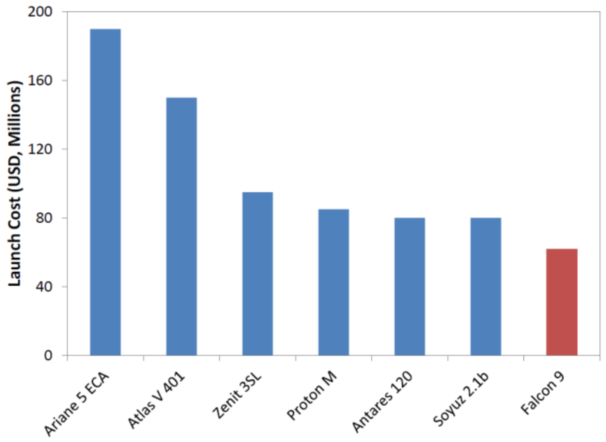

Fig. 3. Medium-lift launch vehicle prices.
Source: [9]

2.1 ELV Launch Price Estimate

Establishing an ELV price estimate for the Falcon 9 is relatively straightforward, as this information is available in the public domain. According to SpaceX [12], a Falcon 9 ELV launch costs USD $ 62 million. Converting this value to FY2020 USD using the inflation factors from [13], results in an ELV price estimate of USD $ 66.2 million.

2.2 Low-maturity RLV Launch Price Estimate

For the purposes of this study, a “low-maturity” RLV launch price assumes both low market and technological maturity. “Low market maturity” refers to a situation in which there is only one RLV operator in the space transportation industry, allowing them to pass some cost savings on to clients, while at the same time retaining a significant portion of the cost savings as increased earnings. Without competition from other low-cost RLVs, the operator can still undercut ELV prices, while maintaining high profit margins.

“Low technological maturity” refers to a situation in which the RLV is only partially reusable. In this situation, the first stage is reused, but other components such as upper stages and payload farings are expendable. Furthermore, reusable booster service life is limited to a low number of flights.

The aforementioned conditions reflect the current state of RLV development – the Falcon 9 is currently the only RLV in commercial operation, and its reusability is currently limited to the booster stage. A 2016 analysis performed by investment bank Jefferies International LLC describes in which the launch price of a Falcon 9 RLV is estimated, under assumptions similar to the aforementioned “low maturity” conditions [14].

Specifically, the analysis described in [14] assumes an expendable launch price of USD $ 61.2 million, a gross margin of 40% on expendable Falcon 9 flights, that the booster represents 75% of total launch costs (based on public statements by SpaceX executives), the booster has a service life of 15 flights, and that SpaceX passes on 50% of reusability cost savings, retaining the other 50% as earnings. Based on these assumptions, the reduced launch price determined in [14] is USD $48.3 million, with SpaceX’s gross margin for an RLV flight increasing to 77%.

However, some of these assumptions have since been proven to be outdated. Specifically, the launch price for an expendable Falcon 9 is now listed as USD $ 62 million, and SpaceX executives have claimed that the booster represents closer to 70% of total launch costs [15]. Thus, it is necessary to modify the analysis described in [14] using these updated figures. This modified analysis process is described below.

The direct cost of an expendable launch can be determined as shown in Equation (1).

$$DC_{ELV} = P_{ELV} \times (1 - GM_{ELV}) \qquad (1)$$

The cost of an expendable first stage can be estimated based on a proportion of the direct cost, as shown in Equation (2)

$$C_{B,ELV} = DC_{ELV} \times R_B \qquad (2)$$

It follows that the recurring launch costs not associated with a reusable booster can be determined as shown in Equation (3).

$$C_R = DC_{ELV} - C_{B,ELV} \qquad (3)$$

The cost of a reusable booster stage can then be estimated as shown in Equation (4).

$$C_{B,RLV} = \frac{C_{B,ELV}}{N_B} \qquad (4)$$

Using this value, the direct cost of a reusable launch can be determined as shown in Equation (5).

$$DC_{RLV} = C_{B,RLV} + C_R \qquad (5)$$

Using the same cost saving assumptions from [14] (i.e. cost savings split evenly between reducing prices for clients, and increasing retained earnings for the operator), the price of an RLV launch can be determined as shown in Equation (6).

$$P_{RLV} = P_{ELV} - 0.5 \times (DC_{ELV} - DC_{RLV}) \qquad (6)$$

Finally, the gross margin for an RLV launch can be determined as shown in Equation (7).

$$GM_{RLV} = \frac{P_{RLV} - DC_{RLV}}{P_{RLV}} \qquad (7)$$

The only difference between this estimate and the analysis described by de Selding [14] is the values used for some of the parameters in Equations (1) – (7) have been updated. The values assigned to these parameters are described in Table 1.

Table 1. Low-maturity RLV launch price estimate analysis input parameters

Parameter	Value (units)	Source
P_{ELV}	USD $62 million (FY2017)	[15]
GM_{ELV}	40%	[14]
R_B	70%	[15]
N_B	15	[14]

Using the data from Table 1 with the solution methods described in Equations (1) – (7), and converting to FY2020 USD results in a low-maturity RLV launch price estimate of USD $ 53.2 million, and a corresponding gross margin for RLV launches of 74.1%. This represents a saving of 19.6% over comparable ELV prices.

2.3 Intermediate maturity RLV Launch Price Estimate

For the purposes of this study, an "intermediate-maturity" RLV launch price assumes high market maturity, but low technological maturity. "High market maturity" refers to a situation in which there are two or more RLV operators in the space transportation industry, resulting in competition which reduces profit margins, and lowers costs for clients. At the same time, the "low technological maturity" assumption remains in effect, indicating that reusable technology would still only extend to a first or booster stage with a short service life. With rival partial RLVs like the Blue Origin New Glenn expected to enter service in the near future [16], competition between SpaceX and Blue Origin will likely result in this "intermediate-maturity" scenario coming to pass.

As demonstrated in Section 2.2, low market maturity can result in significant profit margins. It is assumed that high market maturity will result in profit margins more aligned with industry averages. Economic data indicates that the average gross margins in the U.S. aerospace and defence sector are approximately 20% [17]. Using this lower gross margin value for RLV operations, the analysis described in Section 2.2 can be replicated for a high market maturity scenario. In this case, gross margin is specified as an input and used to determine RLV launch price. Thus, Equations (6) and (7) are replaced with Equation (8).

$$P_{RLV} = \frac{DC_{ELV}}{1 - GM_{RLV}} \qquad (8)$$

The parameter input values used in this analysis are described in Table 2.

Table 2. Intermediate-maturity RLV launch price estimate analysis input parameters

Parameter	Value (units)	Source
P_{ELV}	USD $62 million (FY2017)	[15]
GM_{ELV}	40%	[14]
R_B	70%	[15]
N_B	15	[14]
GM_{RLV}	20%	[17]

Using Equations (1) – (5) and (8), along with the values in Table 2, and converting to FY2020 USD, the intermediate-maturity RLV launch price can be estimated as USD $ 17.5 million. This represents a saving of 73.4% over comparable ELV prices.

2.4 High-maturity RLV Launch Price Estimate

For the purposes of this study, a "high-maturity" RLV launch price assumes both high market and technological maturity. "High technological maturity" refers to a situation in which technology has progressed to a point where the RLV is fully reusable. For the Falcon 9, this would mean a reusable upper stage and payload faring – future developments which SpaceX executives have discussed publicly [18]. High technological maturity will also likely include an extension in reusable component service life. As described in Section 2.3, "high market maturity" refers to a situation in which price competition between RLV operators forces gross margins down to industry-average levels for the aerospace and defence sector.

In order to estimate the direct costs for a "high technological maturity" Falcon 9 RLV, it is necessary to estimate the cost and reuse rates for all three potentially reusable components: the booster stage, the payload faring and the second stage. As described in Section 2.2, the booster stage represents approximately 70% of total launch costs. However, for a technologically mature reusable booster, service life could potentially be extended to 40 reuse flights [19]. SpaceX has stated publicly that the payload faring costs about USD $ 6 million [18]. As a service life for this component has not been established in the public domain, the conservative estimate of 15 reuse flights from [14] is used.

SpaceX consider reusing the second stage of the Falcon to be a stretch goal, and have not publicly described the potential rate of reuse, or the cost of the stage. As a service life for this component has not been established in the public domain, the estimate of 15 reuse flights from [14] is used. The cost of the second stage is estimated based on proportional scaling of the booster stage. Both stages use variants of the Merlin engine – nine of the engines are used in the first stage, and one vacuum-optimized variant is used in the second stage. Rocket engines are typically one of the most expensive components in a launch vehicle stage [3]. Thus, assuming stage costs are roughly proportional to engine costs, the cost of the second stage can be estimated as shown in Equation (9).

$$C_{2,ELV} = \frac{1}{9} \times C_{B,ELV} \tag{9}$$

In order to account for their reuse, it is necessary to determine the reusable costs for the payload faring and second stage, as shown in Equations (10) and (11).

$$C_{F,RLV} = \frac{C_{F,ELV}}{N_F} \tag{10}$$

$$C_{2,RLV} = \frac{C_{2,ELV}}{N_2} \tag{11}$$

The reuse of the faring and second stage, in addition to the booster stage, must be accounted for in determining recurring costs and RLV direct costs. Thus, Equations (3) and (5) must be amended for this analysis, as shown in Equations (12) and (13), respectively.

$$C_R = DC_{ELV} - C_{B,ELV} - C_{F,ELV} - C_{2,ELV} \tag{12}$$

$$DC_{RLV} = C_{B,RLV} + C_{F,RLV} + C_{2,RLV} + C_R \tag{13}$$

The parameter input values used in this analysis are described in Table 3.

Table 3. High-maturity RLV launch price estimate analysis input parameters

Parameter	Value (units)	Source
P_{ELV}	USD $62 million (FY2017)	[15]
FC_{ELV}	USD $6 million (FY2017)	[18]
GM_{ELV}	40%	[14]
R_B	70%	[15]
N_B	40	[19]
N_F	15	[14]
N_2	15	[14]
GM_{RLV}	20%	[17]

Using Equations (1), (2), (4), and (8) – (13), along with the values in Table 3, and converting to FY2020 USD, the high-maturity RLV launch price can be estimated as USD $ 4.8 million. This represents a saving of 92.8% over comparable ELV prices.

3. ADR Mission Cost Estimates

In order to determine the proportional cost savings which RLVs could enable on an ADR mission, it is necessary to estimate the total cost of an ADR mission. Existing architectures for two different ADR missions are used as baselines for these cost estimates: the ADReS-A mission [20], and a foam-based debris removal mission [21]. These missions were selected as baselines due to their detailed mission architectures which have been published in the public domain. These detailed architectures enable cost estimates for these missions to be developed. The cost estimation methodology used in this study is described in this section.

Cost estimates have been established using parametric cost models from [13]. These models use mass breakdowns to estimate the cost of the spacecraft bus, which in turn is used to calculate payload, Integration, Assembly & Test (IA&T), program, Ground Support Equipment (GSE) and operations support costs. Cost estimates are provided for both Research, development, test & evaluation (RDT&E) and Theoretical First Unit (TFU).

Launch Costs are calculated based on the launch mass of the spacecraft, and the various price estimates established in Section 2.The payload capacity to Low Earth Orbit (LEO) for an expendable Falcon 9 is 22,800 kg [12]. This capacity is likely to be lower for RLV flights, due to the need to carry additional propellant for re-entry, descent and landing. Thus, the payload capacity for a Falcon 9 RLV was assumed to be 15,000 kg. It was assumed that, if capacity allowed, multiple ADR spacecraft would be carried on a single launch flight to reduce costs.

This study also assumes that ADR operations are conducted on a commercial basis, and a private sector reduction in RDT&E costs of 20% is applied, as described in [13]. Both systems are scaled to remove 50 individual debris targets over a 10-year period, in order to meet the 5 debris per year goal required to stabilize the debris population [10]. A learning curve is assumed, as described in [13], whereby the total production costs for all spacecraft manufactured under the program are determined based on a gradual decrease in costs from the TFU, as efficiency improves over time. The learning curve formula is shown in Equation (11).

$$C_{SP} = C_{TFU} \times {N_S}^{1-\ln\left(\frac{1}{S}\right)/\ln(2)} \tag{14}$$

3.1 ADReS-A Mission Cost Estimate

The proposed ADReS-A uses a large main spacecraft to rendezvous with expended rocket bodies in LEO, attach a smaller spacecraft, referred to as a "deorbit kit" to the rocket body, and then uses the deorbit kits propulsion system to deorbit the rocket body [20]. The basic mission architecture is shown in Fig. 4. The main spacecraft carries five deorbit kits [20], hence five main spacecraft and 50 deorbit kits would need to be manufactured and launched to meet the specified debris removal goals of 50 targets over a 10-year period.

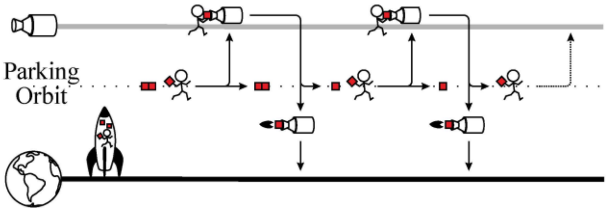

Fig. 4. ADReS-A Mission Architecture. Source: [20]

The total RDT&E and TFU costs of the two types of spacecraft required for this mission have been estimated based on separate estimates for their individual subsystems. Specifically, estimates have been developed for the cost of the structure, Thermal Protection System (TPS), Electrical Power System (EPS), Command & Data Handling (C&DH), Attitude Determination and Control System (ADCS), and propulsion systems, based on parametric cost models from [13]. These cost models use subsystem mass as input parameters. In some cases, estimates for the two spacecraft are based on different cost models, due to the differing scales of the subsystems. All cost models described in this section take inputs in kilograms and give outputs in FY2000 USD.

For the main spacecraft, the RDT&E and TFU costs of the structure are estimated as shown in Equations (15) and (16), respectively.

$$C_{S,R} = 157{,}000 \times {M_S}^{0.83} \tag{15}$$

$$C_{S,T} = 13{,}100 \times M_S \tag{16}$$

For the deorbit kit, the RDT&E and TFU costs of the structure are estimated as shown in Equations (17) and (18), respectively.

$$C_{S,R} = 700 \times [299 \times M_S \times \ln(M_S)] \tag{17}$$

$$C_{S,T} = 300 \times [299 \times M_S \times \ln(M_S)] \tag{18}$$

For the main spacecraft, the RDT&E and TFU costs of the TPS are estimated as shown in Equations (19) and (20), respectively.

$$C_{TPS,R} = 394{,}000 \times {M_{TPS}}^{0.635} \tag{19}$$

$$C_{TPS,T} = 50{,}600 \times {M_{TPS}}^{0.707} \tag{20}$$

For the deorbit kit, the RDT&E and TFU costs of the TPS are estimated as shown in Equations (21) and (22), respectively.

$$C_{TPS,R} = 500 \times \left(246 + 4.2 \times {M_{TPS}}^2\right) \tag{21}$$

$$C_{TPS,T} = 500 \times \left(246 + 4.2 \times {M_{TPS}}^2\right) \tag{22}$$

For both the main spacecraft and the deorbit kit, the RDT&E and TFU costs of the EPS are estimated as shown in Equations (23) and (24), respectively.

$$C_{EPS,R} = 680 \times \left(-926 + 392 \times {M_{EPS}}^{0.72}\right) \tag{23}$$

$$C_{EPS,R} = 320 \times \left(-926 + 392 \times {M_{EPS}}^{0.72}\right) \tag{24}$$

For both the main spacecraft and the deorbit kit, the RDT&E and TFU costs of the C&DH system are estimated as shown in Equations (25) and (26), respectively.

$$C_{CDH,R} = 710 \times \left(484 + 55 \times {M_{CDH}}^{1.35}\right) \tag{25}$$

$$C_{CDH,R} = 290 \times \left(484 + 55 \times {M_{CDH}}^{1.35}\right) \tag{26}$$

For the main spacecraft, the RDT&E and TFU costs of the ADCS are estimated as shown in Equations (27) and (28), respectively.

$$C_{ADC,R} = 464{,}000 \times {M_{ADC}}^{0.867} \quad (27)$$

$$C_{ADC,T} = 293{,}000 \times {M_{ADC}}^{0.777} \quad (28)$$

For the deorbit kit, the RDT&E and TFU costs of the ADCS are estimated as shown in Equations (29) and (30), respectively.

$$C_{ADC,T} = 370 \times \left(1358 + 8.58 \times {M_{ADC}}^{2}\right) \quad (29)$$

$$C_{ADC,T} = 630 \times \left(1358 + 8.58 \times {M_{ADC}}^{2}\right) \quad (30)$$

For both the main spacecraft and the deorbit kit, the RDT&E and TFU costs of the propulsion system are estimated as shown in Equations (31) and (32), respectively.

$$C_{P,R} = 500 \times \left(65.6 + 2.19 \times {M_{SB}}^{1,.261}\right) \quad (31)$$

$$C_{P,R} = 500 \times \left(65.6 + 2.19 \times {M_{SB}}^{1,.261}\right) \quad (32)$$

For both the main spacecraft and the deorbit kit, the RDT&E and TFU costs of the payload are estimated as shown in Equations (33) and (34), respectively.

$$C_{PL,R} = 0.24 \times C_{SB} \quad (33)$$

$$C_{PL,T} = 0.16 \times C_{SB} \quad (34)$$

For both the main spacecraft and the deorbit kit, wraps are applied to the spacecraft bus cost to estimate the various IA&T, program, GSE and operations support costs. These costs for both RDT&E and TFU are estimated as shown in Equations (35) and (36), respectively.

$$C_{W,R} = 0.1805 \times C_{SB} \quad (35)$$

$$C_{W,T} = 0.3145 \times C_{SB} \quad (36)$$

The ADReS-A spacecraft specifications used to develop the cost estimate are detailed in Table 4. Based on the combined total launch mass of both spacecraft (QTY 1 main spacecraft and QTY 5 deorbit kits) of 2,443 kg, it was assumed that six missions could be launched into LEO on a single Falcon 9 flight.

Table 4. ADReS-A spacecraft specifications. Source: [20]

Specification	Main spacecraft	Deorbit kit
Structural mass (kg)	190	35
TPS mass (kg)	36	15
EPS mass (kg)	51	5
C&DH system mass (kg)	27	4
ADCS system mass (kg)	40	5
Spacecraft bus mass (kg)	508	93
Total Launch mass (kg)	933	302

Using the specifications detailed in Table 4, along with the cost models described in this section, the total cost (excluding launch costs) of all missions for a 10-year, 50-target ADR program converted into FY2020 USD has been estimated as $677.8 million. Based on a single mission costing 1/6 of a full launch cost (assuming manifesting of multiple payloads can be used to reduce launch costs), the launch costs have been estimated for an ELV, and for RLVs at various maturity levels, as described in Section 2. The total mission costs for the various launch scenarios are detailed in Table 5.

Table 5. ADReS-A mission total cost estimates.

Launch scenario	Total cost (FY2020 USD, millions)	Cost savings
ELV	788.1	-
Low-maturity RLV	766.5	2.8%
Intermediate-maturity RLV	707.1	11.5%
High-maturity RLV	685.8	14.9%

3.2 Foam-Based Debris Removal Mission Cost Estimate

The proposed foam-based debris removal mission uses a spacecraft to rendezvous with debris in LEO, and spray the target debris with expanding foam, as shown in Fig. 5, which increases the debris drag coefficient and accelerates its orbital decay rate [21]. According to [21], seven spacecraft would need to be launched to meet the specified debris removal goals of 50 targets over a 10-year period.

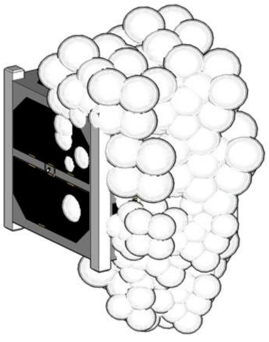

Fig. 5. Expanding foam on a spacecraft. Source: [21]

As with the ADReS-A cost estimate described in Section 3.1, the total RDT&E and TFU costs of the spacecraft have been estimated based on estimates for their individual subsystems. Specifically, estimates have been developed for the cost of the structure, TPS, EPS, C&DH, ADCS, and propulsion systems, based on parametric cost models from [13]. These cost models use subsystem mass as input parameters. All cost models described in this section take inputs in kilograms and give outputs in FY2000 USD.

The costs of the structure are estimated using the same formulas for the ADReS-A main spacecraft cost estimate in Section 3.1, namely Equation (15) for RDT&E costs and Equation (16) for TFU costs. Likewise, the costs of the TPS are estimated using the same formulas for the ADReS-A spacecraft cost estimate in Section 3.1, namely Equation (19)(15) for RDT&E costs and Equation (20) for TFU costs.

The RDT&E and TFU costs of the EPS are estimated as shown in Equations (37) and (38), respectively.

$$C_{EPS,R} = 62{,}700 \times M_{EPS} \tag{37}$$

$$C_{EPS,T} = 112{,}000 \times {M_{EPS}}^{0.763} \tag{38}$$

The costs of the C&DH system are estimated using the same formulas for the ADReS-A spacecraft cost estimate in Section 3.1: Equation (25) for RDT&E costs and Equation (26) for TFU costs. Likewise, the costs of the ADCS are estimated using the same formulas for the ADReS-A main spacecraft cost estimate in Section 3.1, namely Equation (27)(15) for RDT&E costs and Equation (28) for TFU costs.

The RDT&E and TFU costs of the propulsion system are estimated as shown in Equations (39) and (40), respectively.

$$C_{P,R} = 17{,}800 \times {M_P}^{0.75} \tag{39}$$

$$C_{P,T} = 4{,}970 \times {M_P}^{0.823} \tag{40}$$

The costs of the payload are estimated using the same formulas for the ADReS-A spacecraft cost estimate in Section 3.1, namely Equation (33)(15) for RDT&E costs and Equation (34) for TFU costs.

The foam-based debris removal spacecraft specifications used to develop this cost estimate are detailed in Table 6. Based on the total launch mass of the spacecraft of 4,600 kg, it was assumed that three missions could be launched into LEO on a single Falcon 9 flight.

Table 6. foam-based debris removal spacecraft specifications. Source: [21]

Specification	spacecraft
Structural mass (kg)	200
TPS mass (kg)	40
EPS mass (kg)	150
C&DH system mass (kg)	34
ADCS system mass (kg)	100
Propulsion system mass (kg)	178
Total Launch mass (kg)	4,600

Using the specifications detailed in Table 6, along with the cost models described in this section, the total cost (excluding launch costs) of all missions for a 10-year, 50-target ADR program converted into FY2020 USD has been estimated as $650.0 million. Based on a single mission costing 1/3 of a full launch cost (assuming manifesting of multiple payloads can be used to reduce launch costs), the launch costs have been estimated for an ELV, and for RLVs at various maturity levels, as described in Section 2. The total mission costs for the various launch scenarios are detailed in Table 7.

Table 7. foam-based debris removal mission total cost estimates.

Launch scenario	Total cost (FY2020 USD, millions)	Cost savings
ELV	804.4	-
Low-maturity RLV	774.1	3.9%
Intermediate-maturity RLV	691.0	16.4%
High-maturity RLV	661.2	21.7%

4. Consolidated Results

4.1 Launch Price Estimates

The launch price estimates for an ELV, as well as low, intermediate and high maturity RLVs are shown in Fig. 6. RLV price reductions range from 19.6% for a low-maturity RLV to 92.8% for a high-maturity RLV. While a high-maturity (i.e. commercially competitive, fully reusable) RLV might not be feasible with current technology, this analysis indicates that significant cost reductions can be achieved with an intermediate-maturity (i.e. commercially competitive partially reusable) RLV. This result highlights the importance of a competitive RLV market in lowering space transportation costs. A single launch operator developing RLV technology is insufficient. Unless operators are motivated by competition to reduce RLV launch price margins, it is unlikely that significant space transportation cost reductions can be achieved.

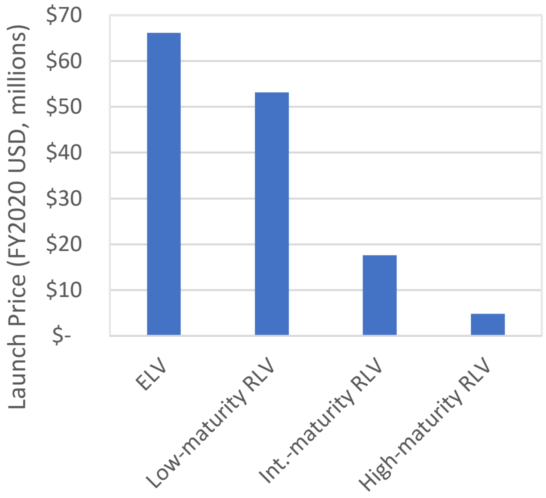

Fig. 6. Launch Price Estimates

4.2 ADR Mission Costs

Total mission costs for the two ADR missions, with different launch price scenarios are shown in Fig. 7. Potential savings from employing RLV technology range from 2.8% for a low-maturity RLV used on the ADReS-A mission, to 21.7% for a high-maturity RLV used on the foam-based debris removal mission. The results indicate that, due to higher total launch mass requirements, greater savings can generally be achieved by using RLVs on the foam-based debris removal mission in comparison to the ADReS-A mission.

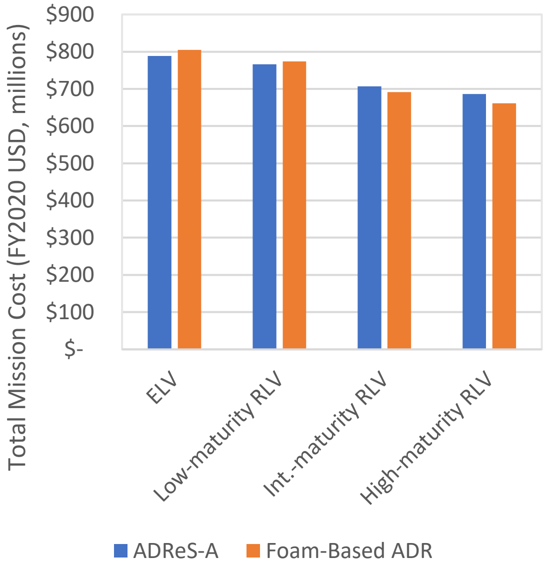

Fig. 7. Total Mission Cost Estimates

As shown in Fig. 7, for ELVs or low-maturity RLVs, the ADReS-A mission has a lower total mission cost. However, for a case where intermediate or high-maturity RLV is used, the foam-based debris removal mission becomes more the lower-cost option. This result demonstrates the impact that RLV technology can have on the feasibility of ADR mission architectures.

5. Other Considerations

The development and proliferation of RLV technology could have significant impacts on the orbital debris environment outside of ADR mission feasibility. For example, expended launch vehicle upper-stages constitute almost half of total debris in orbit by mass [10]. If RLV development reaches the “high-maturity” level described in this paper (i.e. fully reusable), then the act of recovering upper stages for reuse will remove them from the orbital debris environment by definition, eliminating a significant source of debris in LEO.

However, there are also significant orbital debris risks associated with the maturity of RLV technology. By significantly reducing costs, RLVs could lower barriers to accessing space, leading to increased development, and orbital traffic. If this growth is allowed to accelerate without sufficient accounting for long-term sustainability, then the risk of on-orbit collisions and fragmentation could increase significantly. This risk highlights the need to meet any growth in space transportation demand with commensurate legal, policy and regulatory frameworks to mitigate this risk and ensure continued access to space in the future.

6. Conclusions

The study described in this paper attempts to quantify the economic benefit which RLVs could deliver to space transportation industry clients, and subsequently the impact this technology could have on the overall cost of ADR missions. The SpaceX Falcon 9 is used as a baseline for ELV and RLV launch price estimates, and two ADR mission architectures from previous studies were used as baselines for ADR mission cost estimates. The results of this study indicate that RLV technology could significantly reduce ADR mission costs.

As a caveat, it is important to note that factors other than price, such as availability, target orbit and geopolitical concerns can also affect the launch vehicle selection process. Additionally, while the results of the economic analysis in this study provides some quantitative insight into how RLVs could reduce costs and improve feasibility for future ADR missions, it is important to note that errors, while unquantified, could be present in this analysis. Launch price estimates rely heavily on assumptions and public statements from space transportation industry executives, rather than detailed financial breakdowns. ADR mission cost estimates rely on “broad strokes” parametric cost models and preliminary, undetailed mission architectures. While the general trend of the results indicates the magnitude of potential cost reductions through RLV development, only time will tell the exact value of these cost reductions.

Acknowledgements

The authors would like to thank the Secure World Foundation for their support of this study through the SWF 2017 IAC Young Professionals Scholarship.

References

[1] M. Aliberti, M. Tugnoli, The European Launchers between Commerce and Geopolitics, ESPI Report 56, European Space Policy Institute, March 2016.

[2] J.E. Andrews, D.G. Andrews, Designing Reusable Launch Vehicles for Future Space Markets, AIAA 2001-4544, AIAA SPACE 2001 Conference and Exposition, Albuquerque, New Mexico, 2001, 28 – 30 August.

[3] M.M. Ragab, F.M. Cheatwood, S.J. Hughes, A. Lowry, Launch Vehicle Recovery and Reuse, AIAA 2015-4490, AIAA SPACE 2015 Conference and Exposition, Pasadena, California, 2015, 31 August – 2 September.

[4] The Economist, The space shuttle: into the sunset, 30 June 2011, http://www.economist.com/node/18895018, (accessed 13.04.17).

[5] S. Joseph, K. O'Connell, Launch of Space Shuttle Atlantis STS-132, 14 May 2010, https://images.nasa.gov/#/details-sts132-s-059.html, (accessed 19.06.17).

[6] SpaceX, SES-10 Launch - world's first reflight of an orbital class rocket, 30 March 2017, https://www.flickr.com/photos/spacex/32915197674/, (accessed 19.06.17).

[7] SpaceX, SES-10 Mission, March 2017, http://www.spacex.com/sites/spacex/files/finalses10presskit.pdf, (accessed 18.06.17).

[8] SES, SES-10 launched successfully on SpaceX's flight-proven Falcon 9 rocket, 30 March 2017, https://www.ses.com/press-release/ses-10-launched-successfully-spacexs-flight-proven-falcon-9-rocket, (accessed 18.06.17).

[9] Richardson, M., Smart, M., In space, this is the age of reusability, 13 July 2017, https://theconversation.com/in-space-this-is-the-age-of-reusability-77964, (accessed 13.07.17).

[10] Liou, J.-C., An active debris removal parametric study for LEO environment remediation, Adv. Space Res., 47 (11) (2011), 1865 – 1876.

[11] ESA, e.deorbit Implementation Plan, ESA-TEC-SC-TN-2015-007, Issue 1.0, 18 December 2015.

[12] SpaceX, Capabilities & Services, http://www.spacex.com/about/capabilities, (accessed 05.07.17).

[13] H. Apgar, D. Bearden, R. Wong, Cost Modeling, in: W.J. Larson, J.R. Wertz (Eds.), Space Mission Analysis and Design, third ed., Microcosm Press, El Segundo, California & Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 783 – 820.

[14] P.B. de Selding, SpaceX's reusable Falcon 9: What are the real cost savings for customers?, 25 April 2016, http://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/, (accessed 05.07.17).

[15] D. Mosher, Elon Musk spent $1 billion developing SpaceX's reusable rockets — here's how fast he might recoup it all, 21 June 2017, http://www.businessinsider.com/spacex-reusable-rocket-launch-costs-profits-2017-6/#spacexs-go-to-rocket-system-is-the-falcon-9-each-vehicle-stands-229-feet-tall-and-can-loft-a-school-bussize-payload-into-orbit-it-costs-a-customer-about-62-million-to-launch-1, (accessed 05.07.17).

[16] Federal Aviation Administration, The Annual Compendium of Commercial Space Transportation: 2017, August 2017, https://www.faa.gov/about/office_org/headquarters_offices/ast/media/2017_AST_Compendium.pdf, (accessed 01.09.17).

[17] A. Damodaran, Margins by Sector (US), January 2017, http://pages.stern.nyu.edu/~adamodar/New_Home_Page/datafile/margin.html, (accessed 07.07.17).

[18] M. Wall, Elon Musk: SpaceX May Aim for Completely Reusable Falcon 9 Rocket, 30 March 2017, https://www.space.com/36296-spacex-completely-reusable-falcon-9-rocket.html, (accessed 11.07.17).

[19] A. Svitak, NASA, CNES Warn SpaceX of Challenges in Flying Reusable Falcon 9 Rocket, 5 May 2014, http://aviationweek.com/blog/nasa-cnes-warn-spacex-challenges-flying-reusable-falcon-9-rocket, (accessed 11.07.17).

[20] S. Peters, H. Fiedler, R. Forstner, ADReS-A: Mission Architecture for the Removal of SL-8 Rocket Bodies, 2015 IEEE Aerospace Conference, Big Sky, Montana, 2015, 7 – 14 March.

[21] M. Andrenucci, P. Pergola, A. Ruggiero, Active Removal of Space Debris – Expanding foam application for active debris removal, 21 February 2011, http://www.esa.int/gsp/ACT/doc/ARI/ARI%20Study%20Report/ACT-RPT-MAD-ARI-10-6411-Pisa-Active_Removal_of_Space_Debris-Foam.pdf, (accessed 13.07.17).