Space Launch Cost Estimation: Challenges and Opportunities

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Background

Motivation:

- Market dynamics: Uncertainty about commercial launch market's impact on government costs
- Rapid changes in technology and competition
  - e.g., newer launch vehicles with reusable stages
- Interest in developing up-to-date launch cost estimating capability

Key question: What are some key factors affecting launch costs, and what is the state of launch cost estimating?

Analysis Objectives and Approach

Objectives:

- Identify technology & acquisition factors contributing to changes in space launch costs
- Identify current launch cost estimating approaches and potential gaps
- Suggest steps needed to address gaps in launch cost estimation

Method:

- Preliminary literature review
  - ➢Academic journals, industry reports, government documents
- Analysis of open-source historical launch cost data & budget data

Topics

Defining the DoD Launch Enterprise

Launch Costs in Selected Acquisition Reports

Observations about Launch Technology & Cost Reduction

Selected Launch Cost Estimating Approaches

Paths to a Stronger Launch Cost Estimating Capability

Medium and Heavy-lift Vehicles for DoD Payloads are Managed under the National Security Space Launch (NSSL) program

- NSSL: “acquires launch services for heavy and medium lift national security satellites” (Erwin, 2023)
- The NSSL program is an evolution of the Evolved Expendable Launch Vehicle (EELV) program designed to include both reusable & expendable launch vehicles (CRS, 2025)
- Two companies currently have certified launch vehicles:
  United Launch Alliance (ULA), and **SpaceX** (CRS, 2025)
  - ULA currently has the Vulcan
    - Atlas V and Delta IV were also certified but have been retired from NSSL launches
  - SpaceX has two certified launch vehicles, the Falcon 9 and the Falcon Heavy
- SpaceX’s Falcon 9 & Falcon Heavy have reusable first stages
- **Blue Origin** is working to certify its New Glenn launch vehicle & will be competing for task orders along with ULA and SpaceX under NSSL Phase 3 from 2025 to 2029 (Harpley, 2024)
- **Key technology trends are reusability** – reusable first stage and potentially second stage – and Additive Manufacturing/3D printing (Yonekura et al., 2022)

NSSL Rockets

Expendable Vehicles

Atlas V

Delta IV Heavy

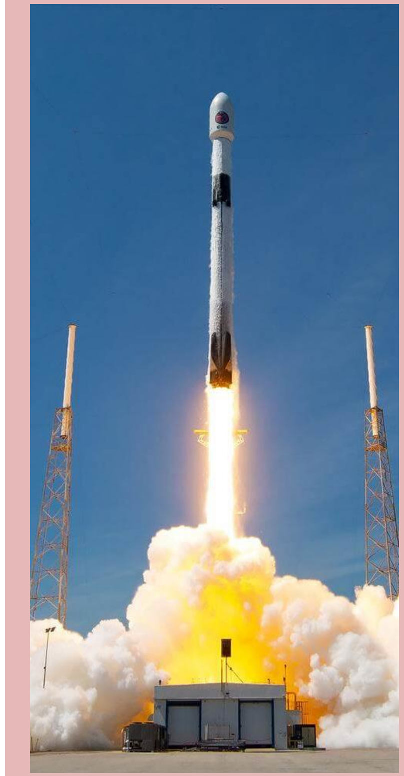
Vulcan

Retired from NSSL

Retired from all launches

certified for NSSL

Vehicles with Reusable First Stage



Falcon 9

Falcon Heavy

New Glenn

Launched on first orbital mission on Jan 16, 2025

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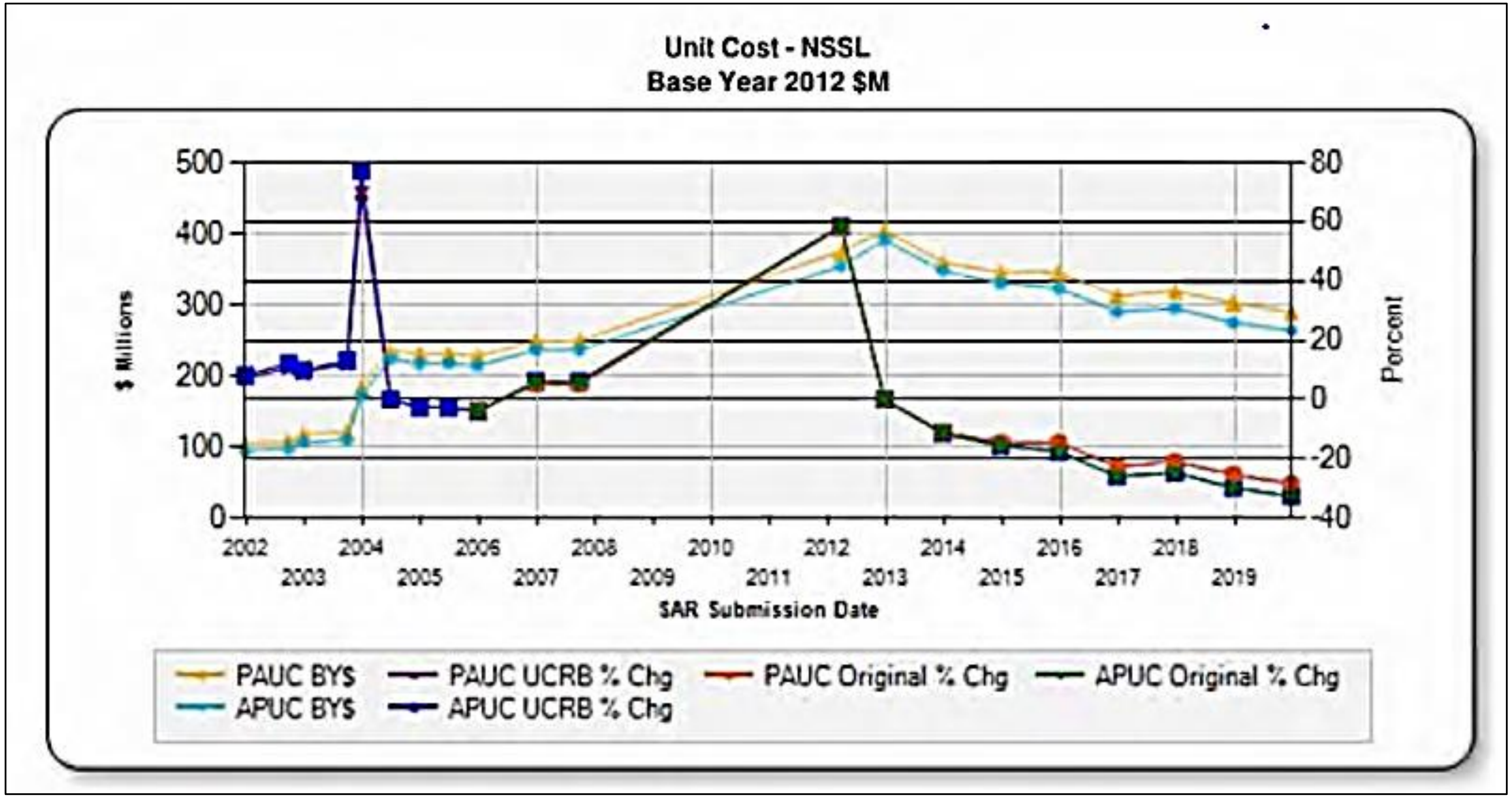
December 2019 SAR Shows How Program Acquisition Cost per Launch (PAUC) and Average Procurement Cost Per Launch (APUC) Changed Over Time

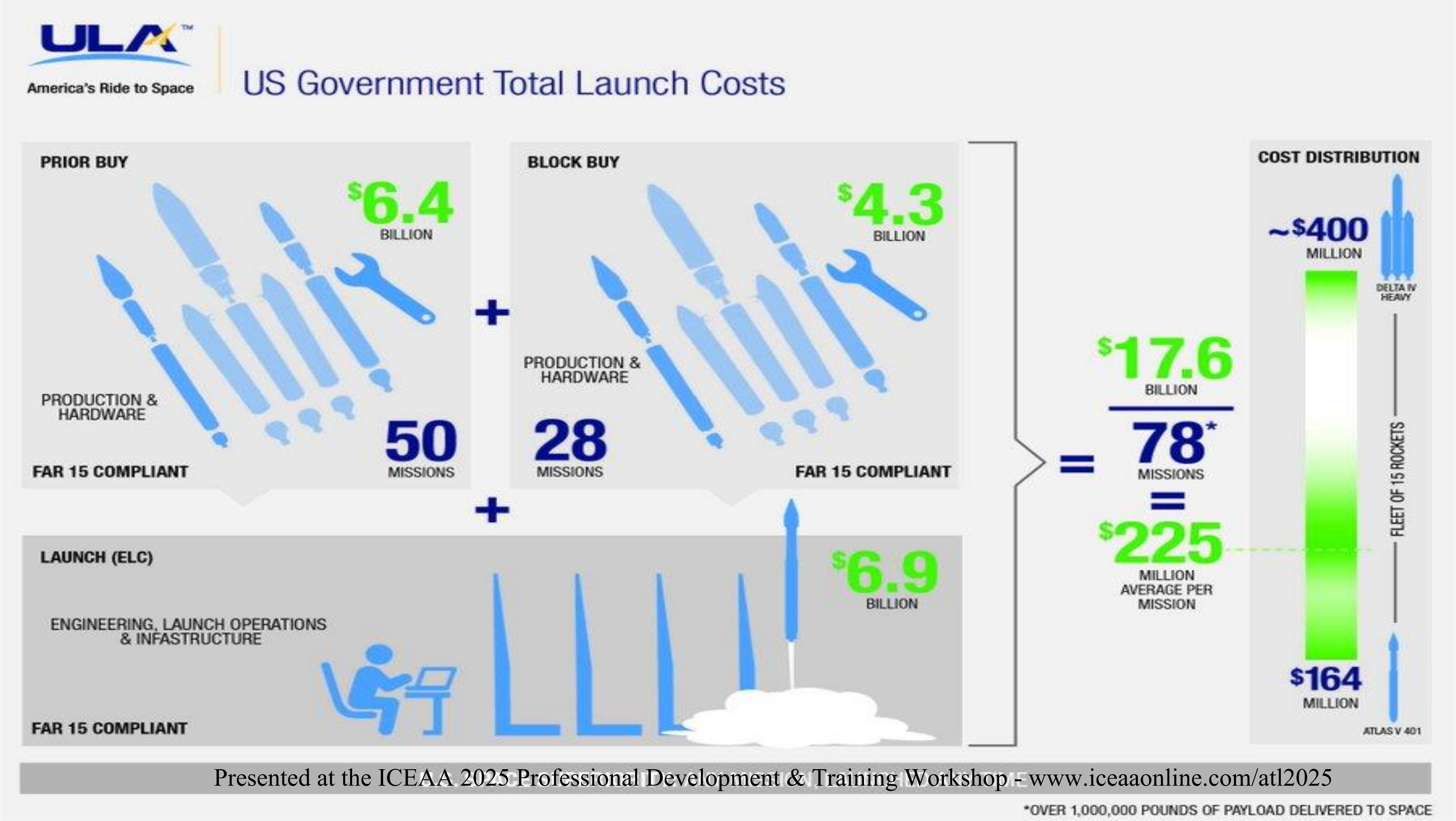


- Factors contributing to lower costs after 2013:
  - In Nov 2011 acquisition strategy changed to incentivize "cost reductions through steady production rates, long-term commitments, and opportunities for competition. "
  - Revised Acquisition Program Baseline was approved in 2013
  - April 2016: "Reintroduced competition and awarded the first FFP competitive contract in over a decade"—the first contract with SpaceX (Falcon 9 launch vehicle)

Dec 2019 SAR for NSSL, p. 36

In 2015 ULA CEO Tony Bruno Provided an Infographic to Illustrate the Basis for ULA Average Cost per Launch Figures

- Add *production & hardware costs* to *engineering, launch operations, & infrastructure costs* and divide by *number of launches* over time.



https://x.com/torybruno/status/584032353787326464

Dec 2023 Selected Acquisition Report Shows Average Procurement Cost Per Launch of $201M

(U) Unit Costs

(U) Current Estimate Compared with Current Baseline

Category (CY$M) Base Year: 2012	Current Baseline 03/22/2022	Current Estimate PB 2025	% Change
Program Acquisition Unit Cost			
Acquisition Cost	64,206.4	54,566.4	
Program Quantity	152	247	
PAUC	422.411	220.917	-47.70%
Average Procurement Unit Cost			
Procurement Cost	59,078.3	49,508.6	
Procurement Quantity	151	246	
APUC	391.247	201.254	-48.56%

- NSSL Program Acquisition Cost per Launch (including RDT&E and Procurement) is about $221M in CY2012 $.
- NSSL Average Procurement Cost per Launch is about $201M in CY2012$.

- 246 launches (163 of which are Space Force launches) purchased with procurement funds
- RDT&E Development Qty of 1 = Heavy-Lift Vehicle (HLV) Operational Launch Service Demonstration (OLSD) launched in Dec 2004
- NSSL Launch services have firm-fixed price launch service contracts
- “Average unit cost figures reported above are a combination of each of multiple launch vehicle configurations and annual launch capability requirements. The average unit cost will vary due to shifts in payload weight and volume, mission-unique services, number of missions per year and other factors.”

https://www.esd.whs.mil/Portals/54/Documents/FOID/Reading%20Room/Selected_Acquisition_Reports/FY_2023_SARS/NSSL_MSAR_Dec_2023.pdf

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Evolution of Rocket Manufacturing Technology

Traditional Methods (1960 - Present)

- Multi-piece welded/riveted construction
- Thick-plate starting stock machined into stiffened structures
- Extensive material waste (e.g. ~500,000 lbs of chips per Space Shuttle External Tank)
- ~1/2 mile of welds per tank requiring meticulous inspection
- Weld lands increase weight by ~5% due to strength loss

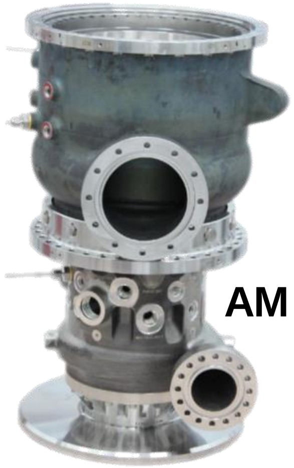
Inefficiencies

- High material waste and cost
- Time-consuming manufacturing and inspection processes
- Reduced structural efficiency due to welds
- Increased risk of failure at weld points

Technological Innovations for Cost Reduction in Aerospace Manufacturing

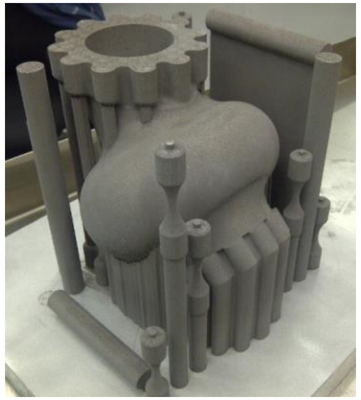
- **Additive Manufacturing (AM)**: AM offers several key advantages that can drive down costs in the long run:
  - **Design Freedom & Complexity:** AM allows for the creation of complex geometries and intricate internal structures, such as lattices, which are difficult or impossible to achieve using traditional methods. This design freedom unlocks opportunities for weight reduction, performance enhancement, and part consolidation.
  - **Reduced Material Waste and Lead Times:** Compared to subtractive manufacturing processes like machining, AM utilizes material more efficiently, generating less waste. Additionally, AM can significantly shorten lead times, particularly for complex parts, which translates to reduced inventory costs and faster production cycles
  - **Part Consolidation:** AM enables the integration of multiple components into a single, optimized part. This consolidation simplifies assembly, reduces the number of parts requiring inspection, and minimizes potential points of failure. The sources provide examples of this in various aerospace applications, including rocket engine components, structural brackets, and heat exchangers

Fuel Injector



AM Turbomachinery

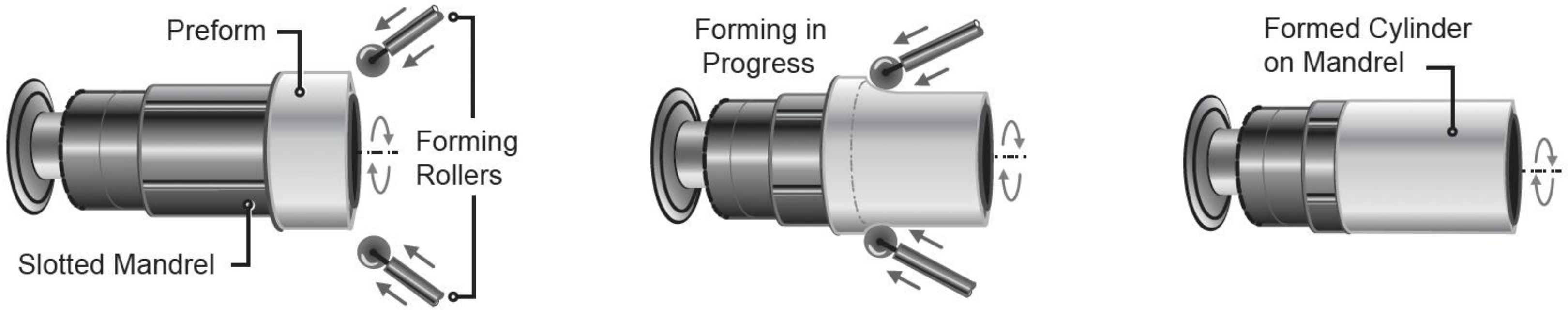
Fuel Turbine Bypass Valve



Large Scale Additive Wire-based Channel Closeout

There are also Single-Piece Manufacturing Approaches that have been applied to fuel/oxidizer tanks

Benefits of New Approaches:
- Reduced manufacturing time and cost
- Improved structural efficiency and performance
- Decreased material waste
- Potential for 5-10% mass savings in cryogenic fuel tanks
- Enables larger payloads and lower cost-per-pound to orbit

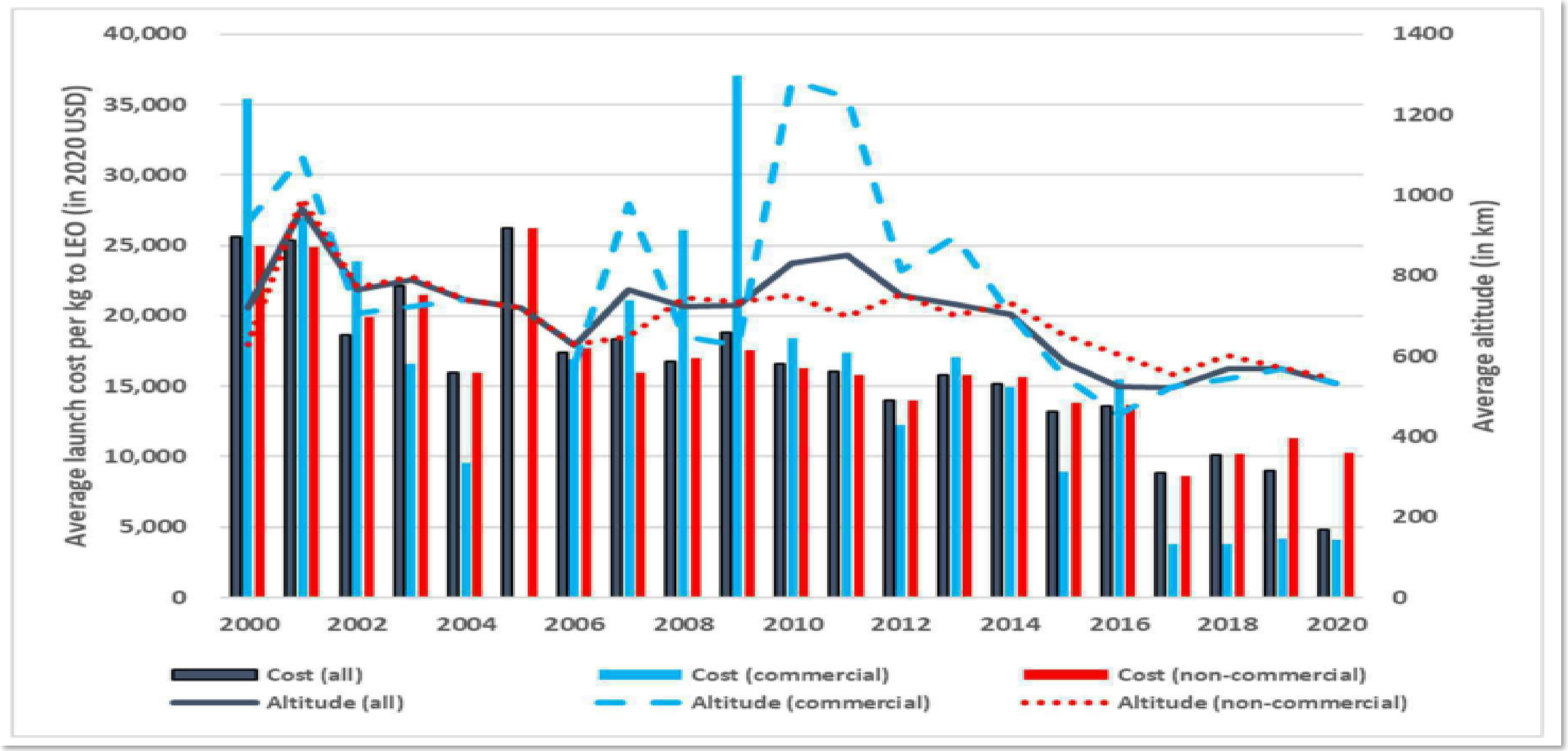


Integrally Stiffened Cylinder (ISC) Process:
- Simultaneously forms thin-walled barrel with internal stiffeners
- Eliminates longitudinal welding and minimizes machining
- Potential for significant cost and mass reduction

Flow-Formed Thick-Walled Cylinders:
- Eliminates longitudinal welding
- Still requires machining for internal stiffeners

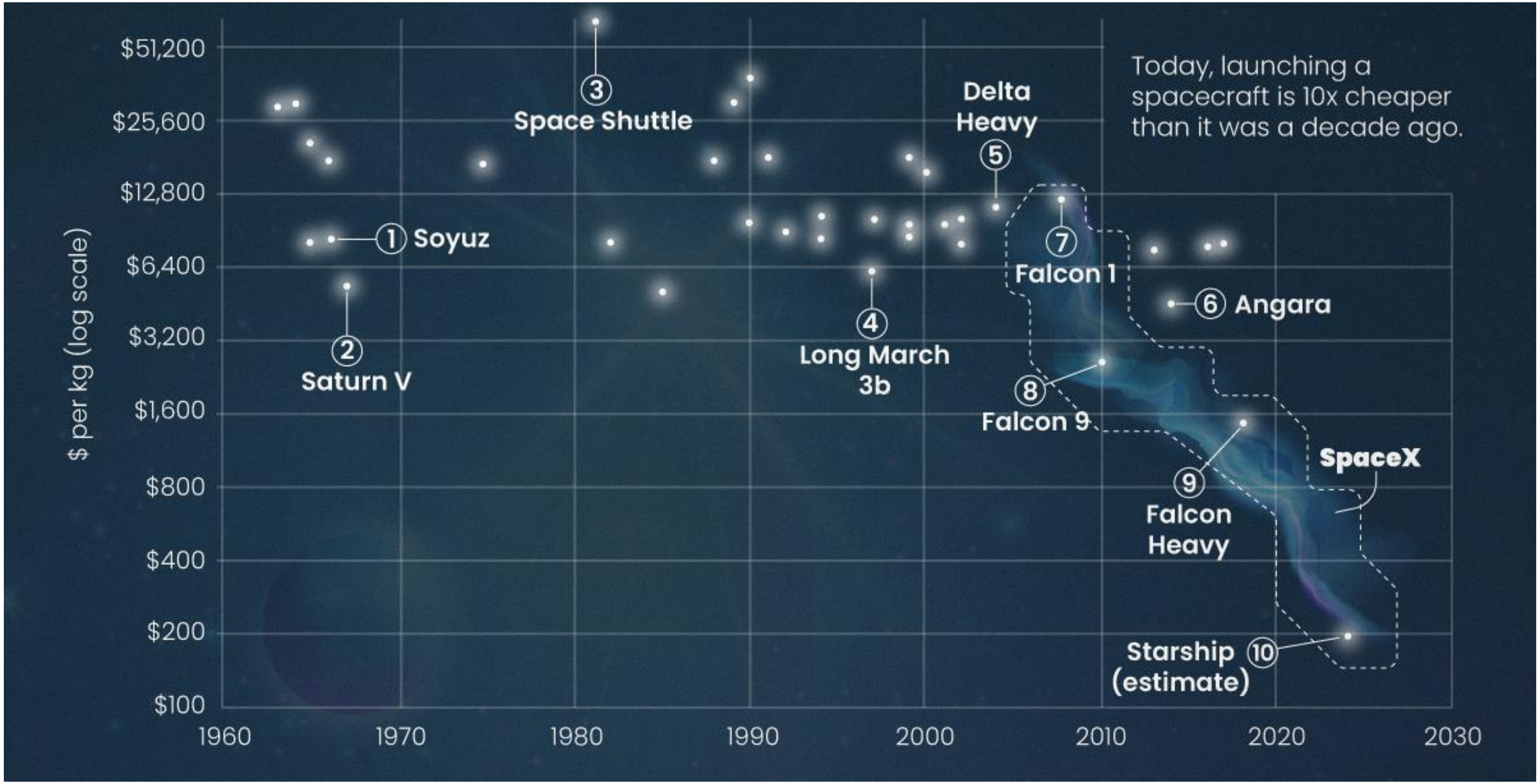
A Recent Study (Adilov et al., 2022) Indicates Launch Costs per Kilogram (Especially Commercial) Decreased Dramatically from 2000-2020

Average per kg launch costs (in 2020 U.S. $) and altitude (2000-2020)



Source: Nodir Adilov & Peter Alexander & Brendan Cunningham & Nikolas Albertson, 2022. "An analysis of launch cost reductions for low Earth orbit satellites," Economics Bulletin, AccessEcon, vol. 42(3), pages 1561-1574.

Others have Also Highlighted Decreasing Launch Costs Over the Past Several Decades



Source: https://www.visualcapitalist.com/the-cost-of-space-flight based on CSIS data (2022).
"Prices have been adjusted for inflation."

Acquisition Improvements Contribute to Launch Cost Reduction

"As everybody knows, the cost of launch has come down dramatically. Where it used to be many hundreds of millions of dollars to get something into space, we're now seeing for larger rockets well under $100 million, and $10 million dollars or less for some of the smaller rockets…"
– Troy Meink, NRO Principal Deputy Director (cited in Hitchens, 2024)

- Contract type: Firm-fixed price, rather than cost plus
- Block buys of launches
- Competition between service providers
  - Two contract vehicles: Launch Service Agreements, Launch Service Procurements
  - NSSL Phase 3 has two lanes of competition:
    - Lane 1, for new providers, has less stringent requirements
    - Lane 2 has stringent security and performance requirements
- Ridesharing

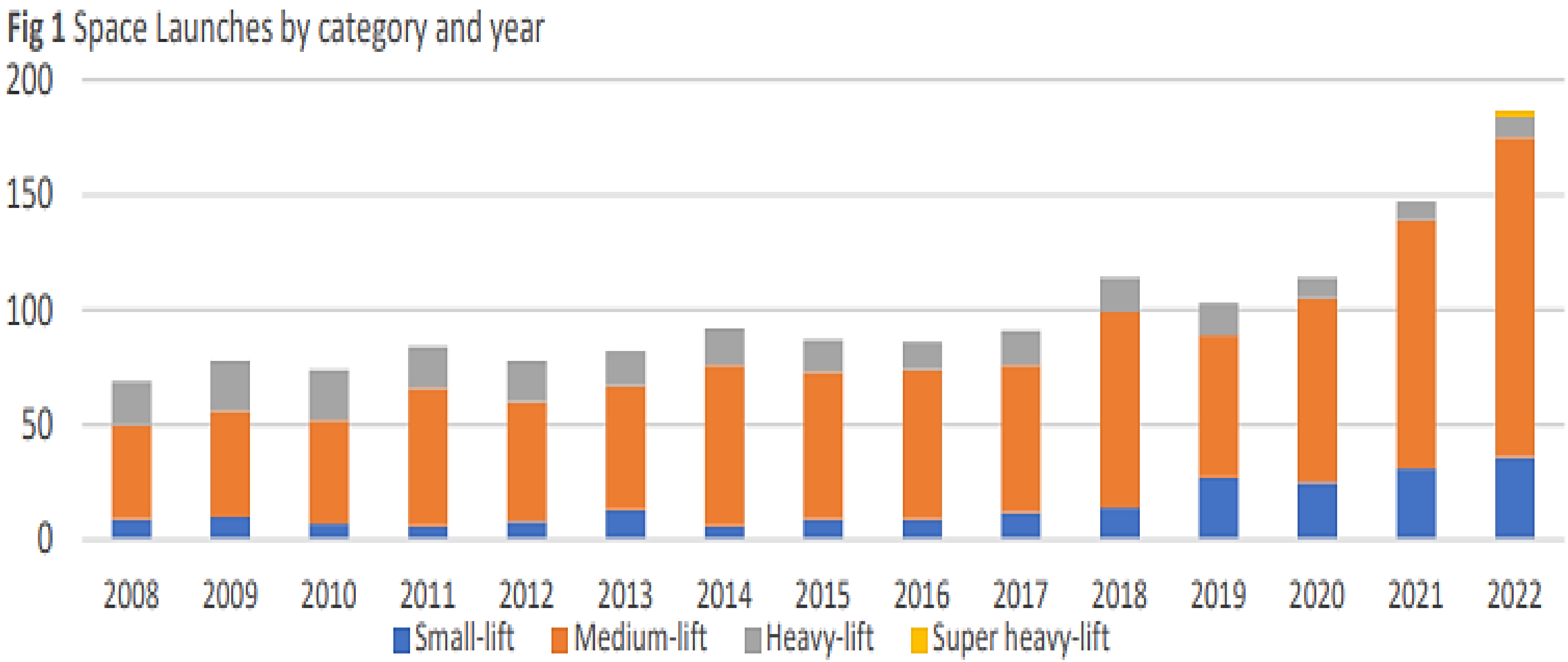
Sources: CRS (2023); Albon (2024); Urban (2023), Adilov et al. (2022); National Security Space Launch > Los Angeles Air Force Base > Display (spaceforce.mil)

Operability Improvements Contribute to Launch Cost Reduction

- Re-use: “SpaceX is among the cheapest services today because the company reuses its boosters and fairings, which make up 60% and 10% of the manufacturing costs, respectively (as reported by CNBC)” (Urban, 2023)
- Common components & infrastructure
- Standardization (of payload interfaces, launch pads)
- Reduction in on-pad processing

CRS (2023); Albon (2024); Urban (2023), National Security Space Launch > Los Angeles Air Force Base > Display (spaceforce.mil)

The Number of Space Launches is Increasing



Sources: Semanik & Crotty (2023), U.S. Private Space Launch Industry is Out of this World (usitc.gov) calculated using data from Krebs (2024) Orbital Launches of 2023 - Gunter's Space Page (skyrocket.de)

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What is Launch Cost? Definitions vary….

- Price a customer pays to put a payload (e.g., satellite or spacecraft) into orbit
  - Typically specified in $ per kilogram of payload or $ per launch
- “vehicle costs and operations costs at the launch location” (Wertz & Larson, 2010, p. 801)
- CSIS Aerospace Security Project indicates their per-kilogram launch cost is typically “unit flyaway cost,” including direct and indirect manufacturing costs, associated overhead, recurring engineering, sustaining, tooling, and quality control
- Perspective paper from Kirtland AFB (Kuennen et al., 2004) noted that the flyaway cost of a launch service includes launch vehicle contractor costs, range costs, launch site facilities costs, launch agency costs

General Launch Cost Estimating Observations

- Launch costs (in $/kg) tend to depend on:
  - Target orbit (LEO, MEO, GTO, GEO, xGEO, interplanetary)
    - e.g., Swan (2024) found that launch cost per kg of payload increases exponentially with mission Delta V requirement
  - Payload mass (larger payloads need larger rockets – but cost less *per kg* due to economies of scale)
    - As Jones (2018, p. 2) noted, "Smaller payloads, payload accommodation systems, and limited payload volume often increase the launch cost per kilogram."
    - McCartney et al. (2006) noted that for expensive payloads (about $1B), launch costs are 10% to 20% of total vehicle and payload cost; for small payloads, launch costs are about 50% of total cost
  - Launch vehicle
    - Roberts (2022): "Some critical differences between launch vehicles, like total lift capability and whether any of their components are designed to be reused, may lead to drastically different launch costs."
  - Complexity of payload integration
    - Due to high integration costs, NASA s is seeking to develop a Universal Payload Interface

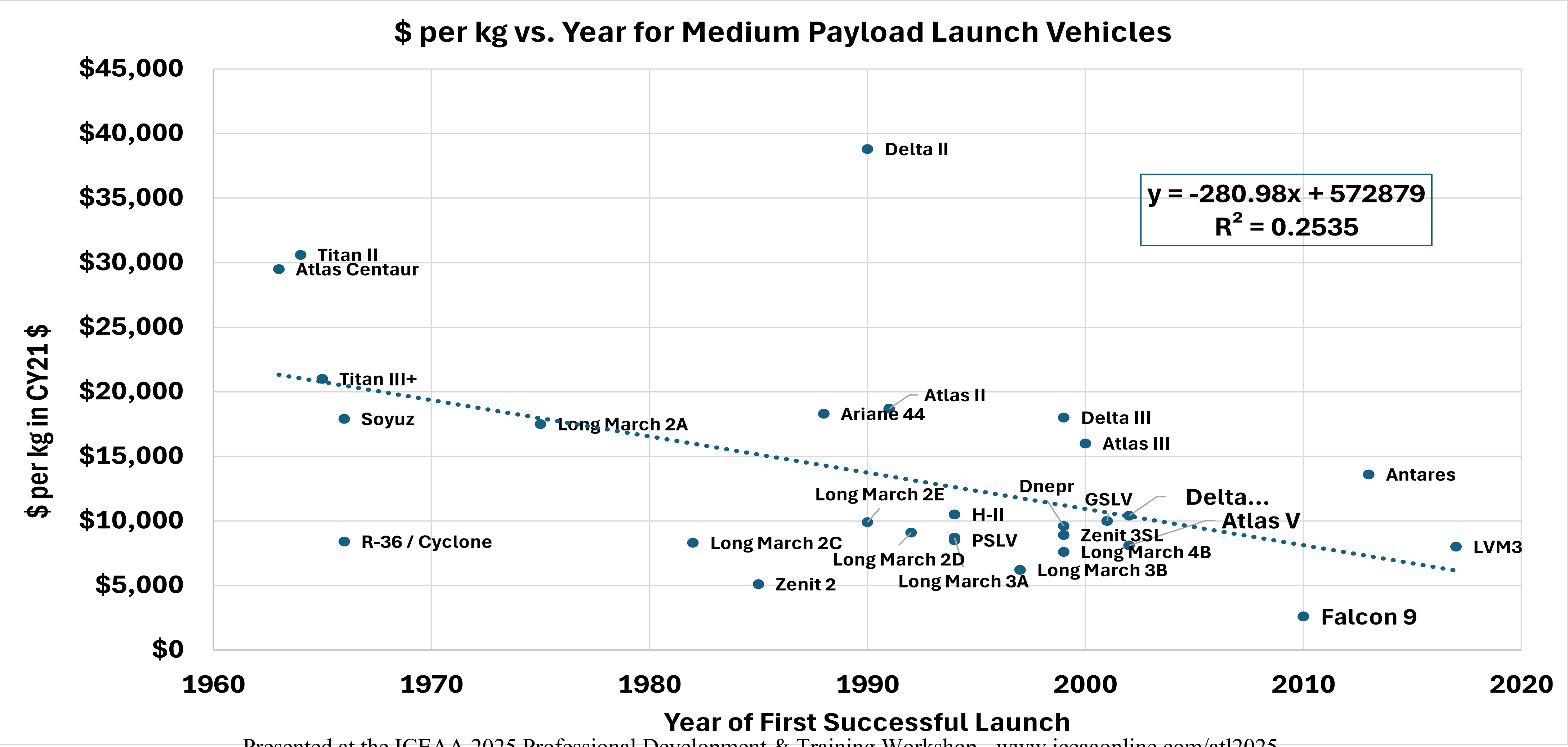
General Launch Cost Estimating Observations

- SpaceX's Falcon 9, with reusable first stage, has by far the lowest launch cost per kg to LEO for typical payloads (~$2,700/kg) (Davis, 2024)
  - It also has the highest reliability and highest launch rate of all current launch vehicles.
- The SpaceX "Starship," expected to be fully reusable, could further reduce this by an order of magnitude
  - SpaceX is reportedly forecasting a cost of $200 per kg (Oleson, 2023; Davis, 2024)

Source: Davis (2024)

Downward Trend in $ per kg is Statistically Significant for Medium Payload Launch Vehicles

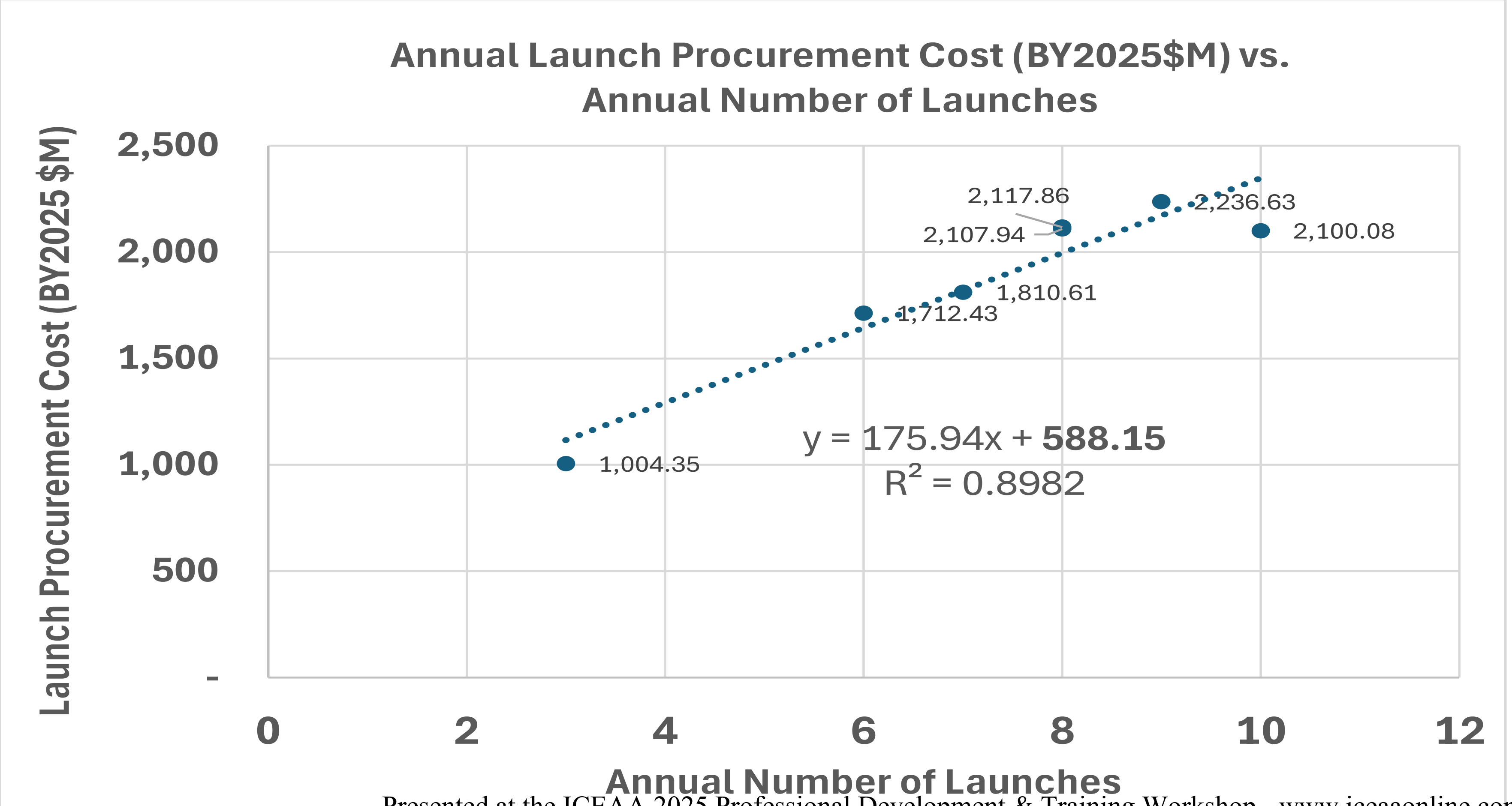
- Data show negative trend with significant R-square for N=28 medium payload vehicles
- Sample size was smaller & R-square was negligible for small and large payload launch vehicles



Source: RAND plot of data from https://ourworldindata.org/grapher/cost-space-launches-low-earth-orbit;

CER based on President’s Budget Data Could Help Predict Annual Fixed & Variable Launch Procurement Costs, given Launch Quantity

Initial analysis of relationship between launch procurement costs and annual launch quantity (from 2025 President’s Budget Data) suggests that, on average, annual NSSL launch procurement costs include about \$588M in fixed costs and \$176M in variable (“per launch” costs)



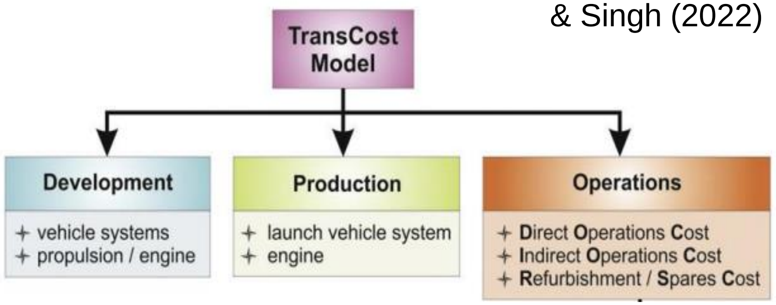
Data were Then-Year Budget Amounts, Converted to BY 2025 from 2023 to 2029

CER was result or regressing BY2025 \$ amounts on number of launches in those years
N=7

TRANSCOST Model Uses Parametric Approach to Estimate Launch Vehicle Cost and Cost Per Flight, but Most Recent Update was in 2013

- TRANSCOST Model (Koelle, 2007, 2013) has three submodels:
  - development cost, vehicle cost, & ground and flight operations
- Estimates man-years (rather than $) based on historical data prior to 2013
- For top-down analysis, with system-level CERs for "initial conceptual design phase of space transportation systems"
  - Development (non-recurring) cost submodel
  - Vehicle (recurring) cost submodel
  - Ground and flight operations submodel

Diagram from Stappert & Singh (2022)



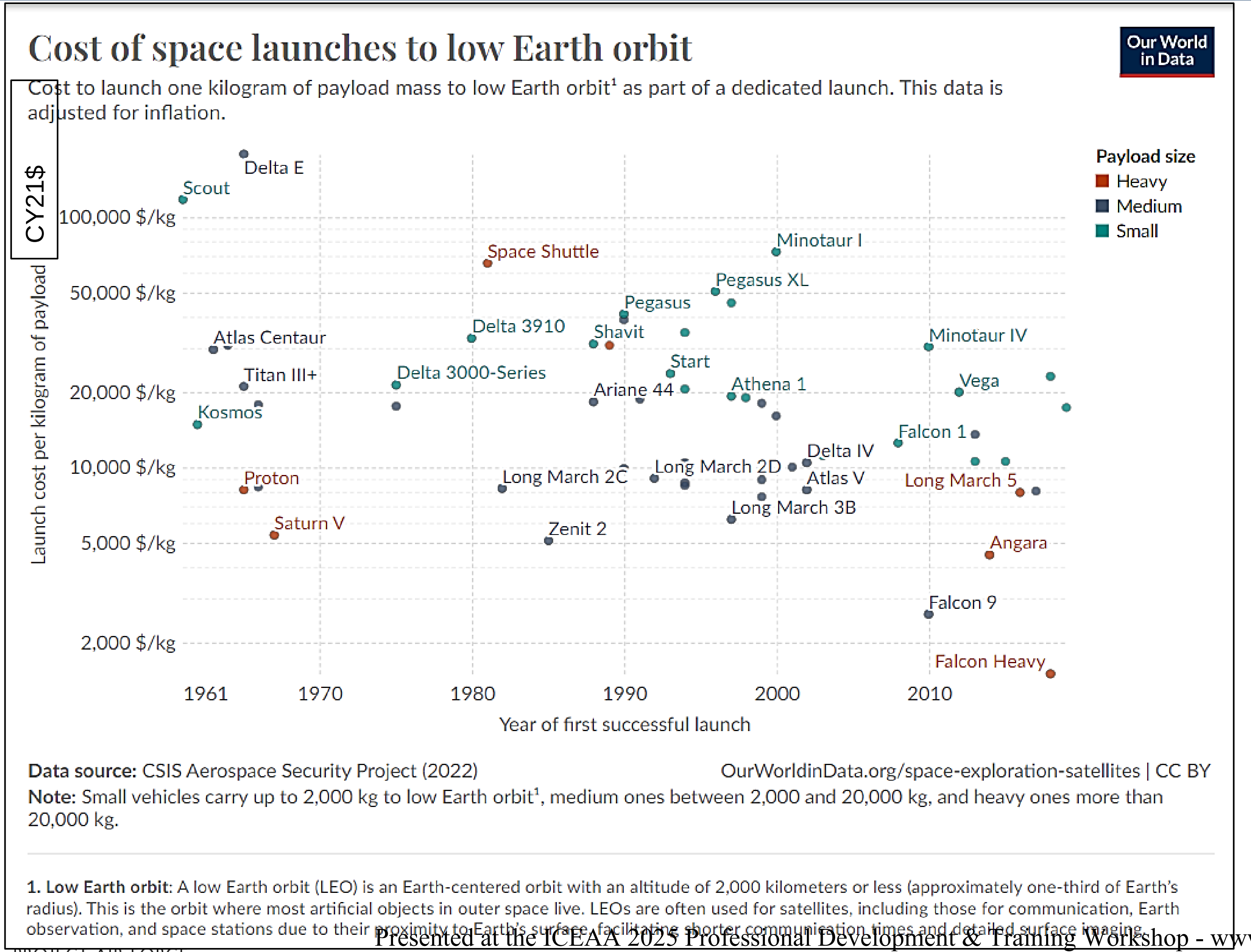
- Predictor variable in most of the CERs is mass of system or unit – typically in the format $C = a \cdot M^{x}$

where C = cost, a = system-specific constant value, M = mass in kg, x = system-specific cost-to-mass sensitivity factor.

NAFCOM also Estimates Launch Costs with CERs – but May Not Yield Accurate Estimates for Some Newer Launch Vehicles

- NASA/Air Force Cost Model (NAFCOM) uses CERs based on historical data to predict costs of launch vehicles in early development
- Includes data from historical NASA and Air Force space projects & estimates development and production costs (Smart, 2009)
- Most recent version may be from 2012 (NAFCOM12)
  - A 2014 briefing (Prince et al., 2014) indicated Project Cost Estimating Capability (PCEC) was being developed by NASA to replace NAFCOM due to new estimating needs
- NAFCOM prediction of Falcon 9 development cost was “more than 10 times the amount SpaceX actually spent” (Allen & Goldston, 2024)

For Newer Launch Vehicles, Analogy Method May be Useful



Analogy method:

- Find launch cost data for similar launch vehicle
- Adjust for differences (e.g., in payload capacity)
- Estimate new vehicle's launch cost

Sources: https://ourworldindata.org/grapher/cost-space-launches-low-earth-orbit; https://aerospace.csis.org/data/space-launch-to-low-earth-orbit-how-much-does-it-cost/

For example, Oleson (2023) Suggested Using Falcon 9 as an Analog for New Glenn

From Oleson (2023):

New Glenn presents a different challenge. There are no data available on its internal costs or pricing strategy, on any need to cover sunk costs, or on any possible discounts. This is a testament to the security of Blue Origin's operations. In this data vacuum, we are left to form estimates by analogy. Arguing that the New Glenn configuration of a reusable first stage with an expendable second stage is similar to the Falcon 9 configuration suggests that a similar price would be appropriate. In the absence of any other information, there's no reason not to use the Falcon 9 price of $67 million as New Glenn's starting point.

New Glenn features projected in 2022

New Glenn	
Size	
Height	322 ft (98 m)
Diameter	23ft (7 m)
Payload Capacity	
LEO	99,000 lbs
GTO	30,000 lbs
Height	58.5ft (17.8m)
Diameter	20ft (6.2m)
Volume	16,184 ft^3 (458m^3)
Thrust	
1st Stage	3.85M lbf
2nd Stage	0.32M lbf

Falcon 9	
Size	
height	229.6 ft
Diameter	12 ft
Payload capacity	
LEO	50,265 lb
GTO	18,300 lb

Sources: https://www.iceaaonline.com/wp-content/uploads/2022/06/TT09-Timm-Superheavy-Launch.pdf, https://www.spacex.com/vehicles/falcon-9/

Launch Cost Estimating Challenges

- Changes in launch technology and acquisition approaches may make CERs based on historical data less accurate
  - Existing CERs are largely based on "historical vehicles produced through government contracting, rather than the commercial approach used by SpaceX" (Wilken et al., 2025)
  - Reuse could result in
    - Reduced production cost (e.g., SpaceX reuses boosters & fairings, which are reportedly 70% of manufacturing costs (Choucair, 2023)
    - greater inspection, testing, & repair costs (Kang, Jo, Choi, Yang, 2025)
    - "hardware, additional infrastructure and personnel to recover or land the stage"(Stappert et al., 2022)
- Data access constraints (e.g., proprietary data)
- Different interpretations of "launch cost" (Roberts, 2022)

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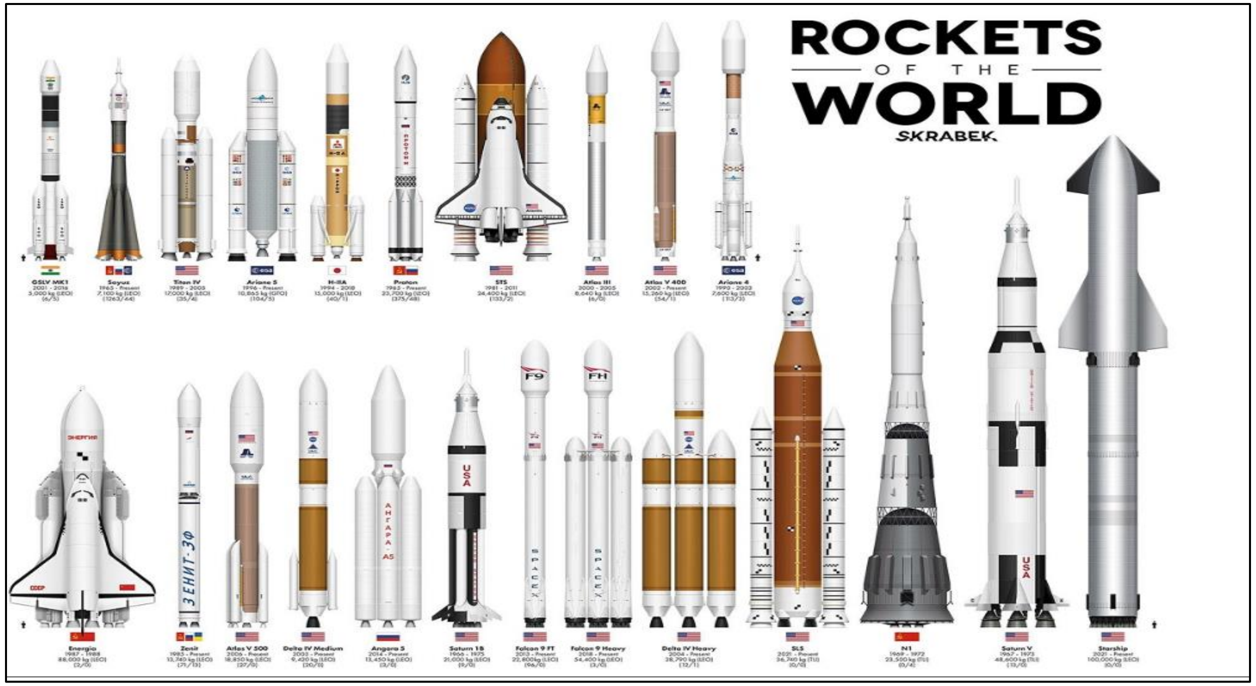
Paths Toward a Stronger Launch Cost Estimating Capability

- Develop/maintain a database of launch vehicles, characteristics, and cost per launch
  - Potential readily accessible data:
    - USAspending.gov
    - Planetary Exploration Budget Dataset
    - Adilov et al. (2022) developed launch dataset from open sources including the Union of Concerned Scientists, the CSIS Aerospace Security Project, and GAO



Source of graphic: https://www.visualcapitalist.com/comparing-the-size-of-the-worlds-rockets-past-and-present/
Source was also used in an NRO briefing: https://www.iceaaonline.com/wp-content/uploads/2022/06/TT09-Timm-Superheavy-Launch.pdf

Paths Toward a Stronger Launch Cost Estimating Capability

- Move toward standard launch cost definition in estimating community
- Develop new CERs for launch cost elements
  - Account for re-use of launch vehicles and other new technologies
- Seek broad SME input on rules of thumb via survey or focus groups
  - What updates, if any, are needed?
- Generate engineering (build-up) estimates of launch vehicles
- Other?

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