Halfway to anywhere: Long-term trends in space transportation cost

Fabian Eilingsfeld
PRICE Systems Ltd.

2016 International Training Symposium of the International Cost Estimating and Analysis Association (ICEAA)

Bristol, England
19 October 2016

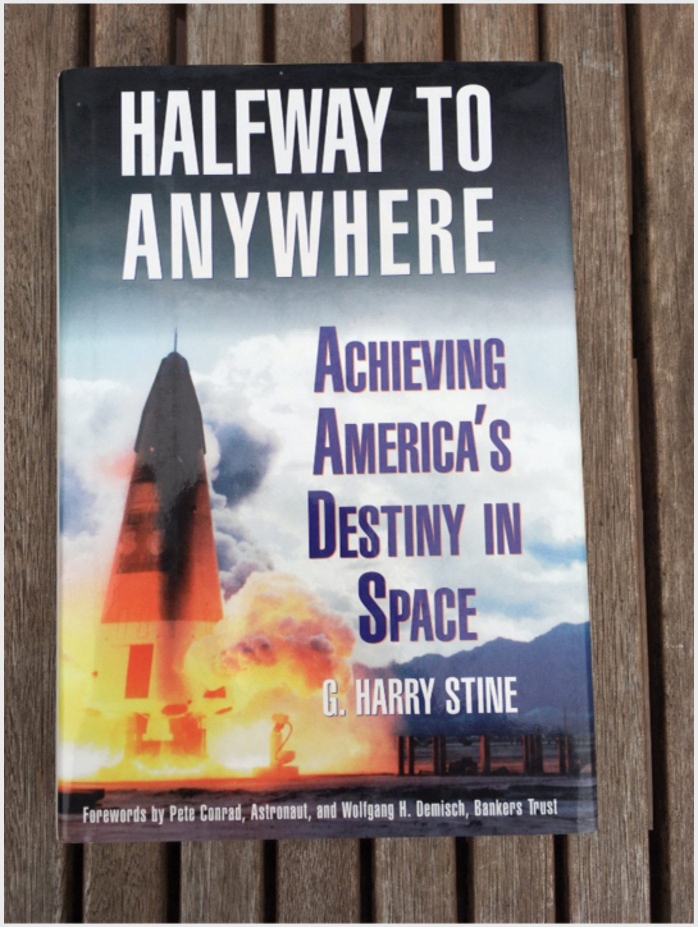
Picture Credit: Adrian Mann

In 1950, Robert A. Heinlein delivered a quote that still resonates with rocket scientists today

PRICE

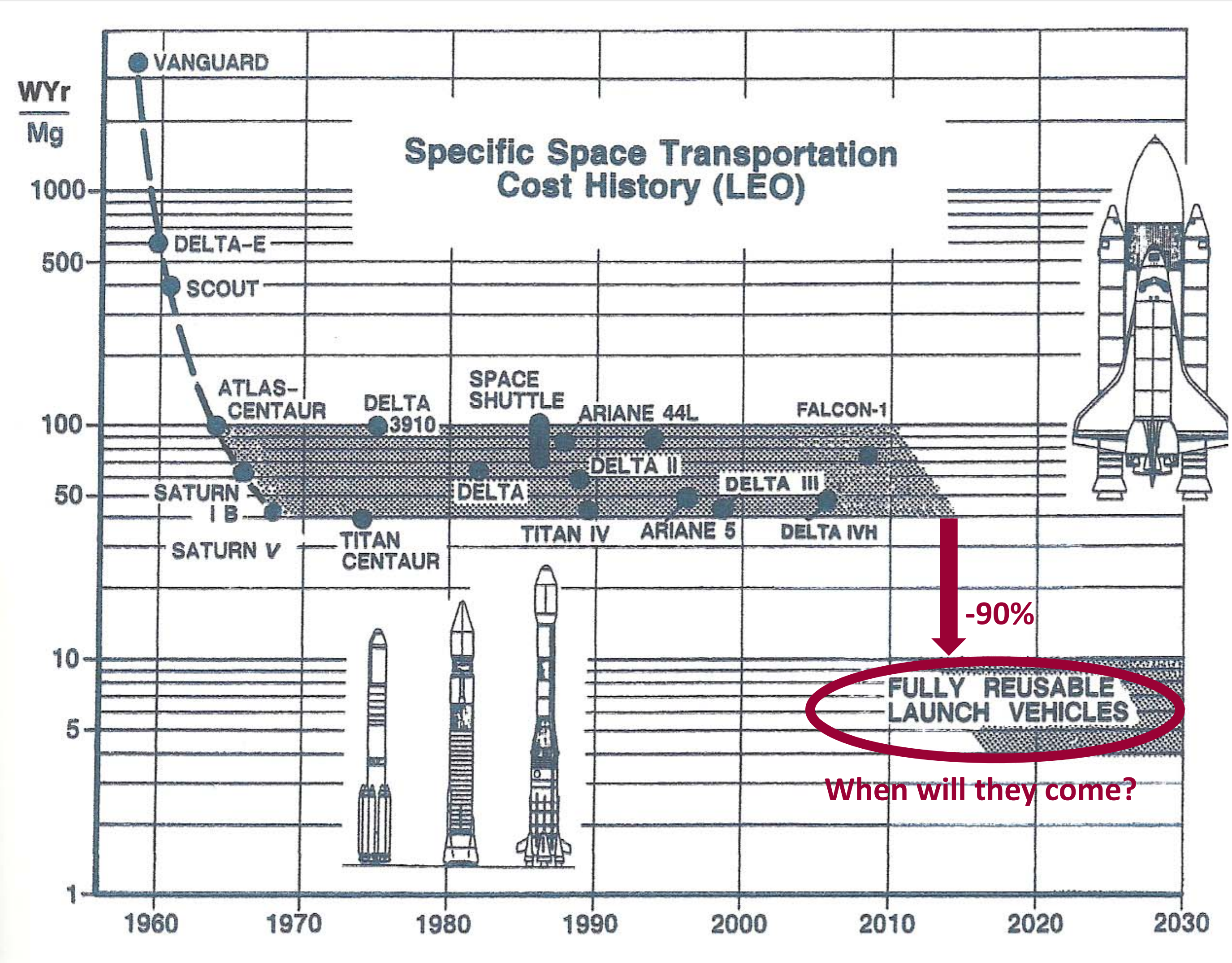
»Get to low-earth orbit and you're halfway to anywhere in the solar system.«

—Robert A. Heinlein



- G. Harry Stine used »Halfway to Anywhere« as a book title in 1996.
- The book was intended as a manifesto for the then-impending space revolution brought about by Single-Stage-to-Orbit (SSTO) launch vehicles.
- Tagline: »Commercial spaceships that operate like airliners are possible and profitable and ***Halfway to Anywhere*** tells how and why.«

Still halfway there, 20 years later: Specific space transportation costs have been stagnating since the Apollo days



- 1958–1968: steep decrease, owing to introduction of cryogenic upper stages and general trend towards larger payload capacity (»the law of scale«)
- After that, not much has changed
- Variations can be attributed to differences in vehicle size and annual flight rate
- The spaceflight revolution is still pending!

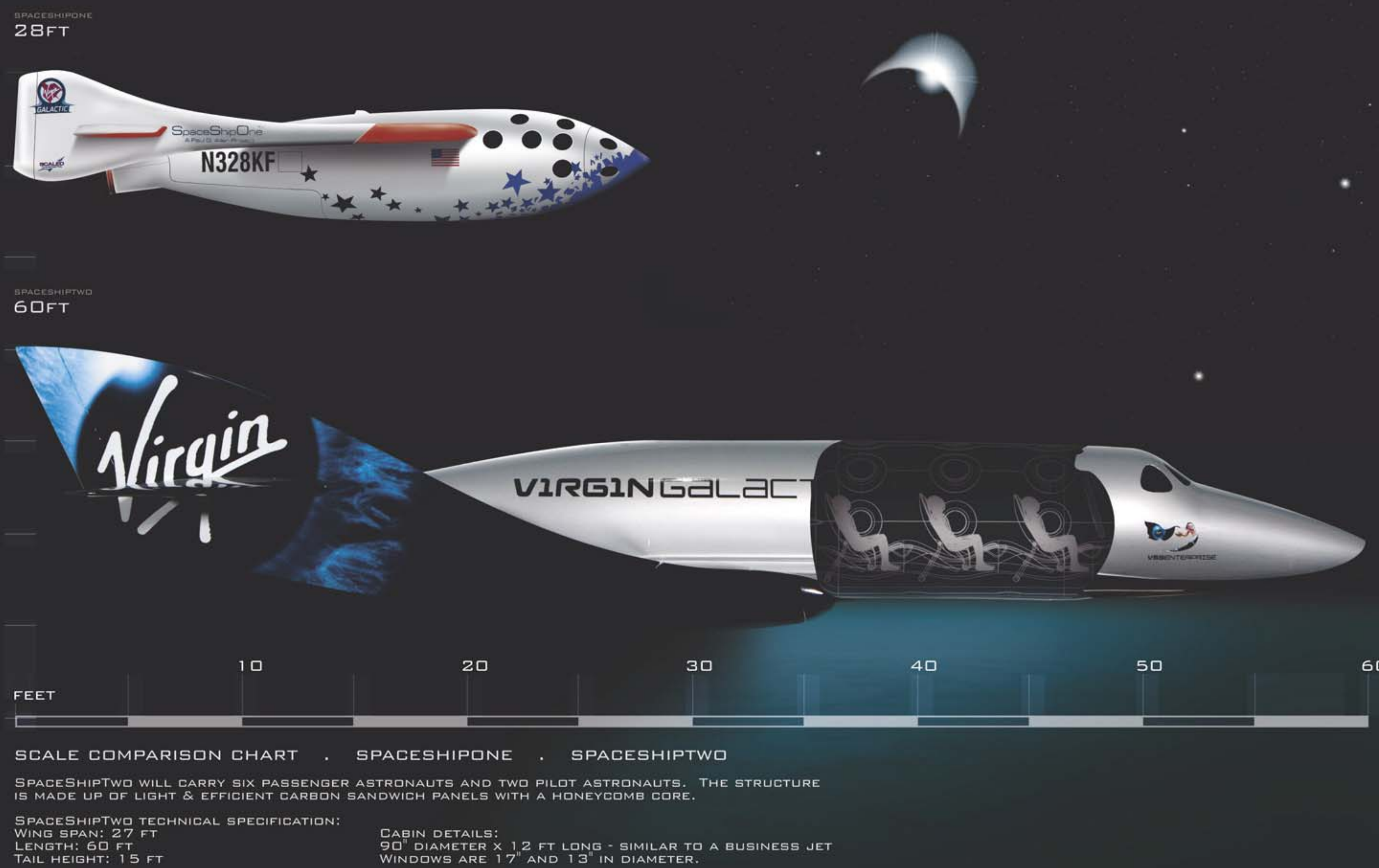
Source: Koelle, TRANSCOST, 2010.

PRICE

1. The (R)Evolution of Space Transportation

The revolution as promised in the 1990s has not happened. Yet, there are still projects that seek to expand the frontier of spaceflight by evolving existing technologies.

Case #1, Suborbital: Virgin Galactic's SpaceshipTwo

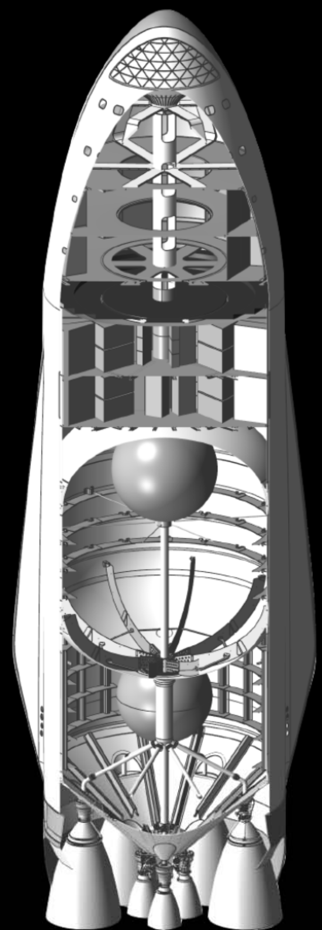


GALACTIC Picture Credit: © 2014 Virgin Galactic Inc., http://virgingalactic.com/gallery/ss2/

Case #2, Beyond Low Earth Orbit: NASA’s Space Launch System (SLS), Block 1

Picture Credit: http://www.nasa.gov/exploration/systems/sls/sls-pdr.html

Case #3, Mars: SpaceX's Interplanetary Spaceship



Length	49.5 m
Max Diameter	17 m
Raptor Engines	3 Sea-Level - 361s Isp
	6 Vacuum - 382s Isp
Vacuum Thrust	31 MN
Propellant Mass	Ship: 1,950 t
	Tanker: 2,500 t
Dry Mass	Ship: 150 t
	Tanker: 90 t
Cargo/Prop to LEO	Ship: 300 t
	Tanker: 380 t
Cargo to Mars	450 t (with transfer on orbit)

Long term goal of 100+ passengers/ship

$140 per kg to Mars!

http://virgingalactic.com/gallery/ss2/

Picture Credit: © 2016 Space Exploration Technologies Corp., http://www.spacex.com/sites/spacex/files/mars_presentation.pdf

2. The Cost and Price of Space Transportation

**Space transportation is an expensive service.
Yet its cost and pricing are deemed intransparent by many observers.**

"Launch Cost" is not what people think

PRICE

- What is launch cost?

The amount charged for a launch vehicle as it goes out the factory door ("flyaway price")?

The amount charged for a "turnkey" launch service, comprising the launch vehicle itself, the cost for ground operations, vehicle setup, propellants, launch control, range safety and the like?

- The total cost of flying to space is more than just the cost of the launch itself!
- There has been a lot of confusion regarding the correct definition of launch cost, or rather the "cost per flight"
- In 1998, the International Academy of Astronautics (IAA) approved the current version of the "Cost per Flight" definition

The IAA's basic Cost/Price per Flight structure comprises five cost categories

PRICE

1. Vehicle Cost (VRC)

- (1A) Vehicle Recurring Cost (expendable vehicles only)
- (1B) Amortization Share of Vehicle Procurement Cost
- (1C) Expendable Elements Cost
- (2) Refurbishment and Spares Cost

2. Direct Operations Cost (DOC)

- (3) Prelaunch Ground Operations Cost
- (4) Flight and Mission Operations Cost
- (5) Propellants, Fluids and Consumables
- (6) Ground Transportation and Recovery Cost
- (7) Launch Facilities User Fee
- (8) Public Damage Insurance Fee
- (9A) Vehicle Failure Impact Charge (expendable vehicles only)
- (9B) Mission Abort and Premature Vehicle Loss Charge
- (10) Other Direct Operations Charges (taxes, fees)

3. Indirect Operations Cost (IOC)

- (11) Program Administration and System Management Charge
- (12) Marketing, Customer Relations and Contracts Office Charge
- (13) Technical Systems Support Charge (incl. spares administration)
- (14) Launch/Landing Site and Range Cost

4. Business Charges (BC)

- (15) Development Cost Amortization Charge
- (16) Nominal Profit

5. Insurance Cost (IC: optional)

- (17) Insurance against Launch Failure
- (18) Insurance against Payload Loss

Source: International Academy of Astronautics (IAA), 1998.

Cost per Flight (CpF) does not equal Price per Flight (PpF); and it doesn't stop there …

PRICE

1. Vehicle Cost (VRC)

\+ *2. Direct Operations Cost (DOC)*

\+ *3. Indirect Operations Cost (IOC)*

= Total Cost per Flight (CpF) → **This, ideally, is what it costs the launch provider to offer the service.**

\+ *4. Business Charges (BC)*

= Price per Flight (PpF) → **This is what the buyer actually pays to the launch provider.**

\+ *5. Insurance Cost (IC: optional)*

= Complete User Cost → **This is what the buyer pays in total for the launch.**

Source: International Academy of Astronautics (IAA), 1998.

There are many complicating factors in determining »real« launch cost

Launch Vehicle Recurring Cost (RC)	▪ Actual unit cost is subject to learning during production ▪ Learning effects depend on manufacturing processes, which may be unknown ▪ Average unit cost is subject to lot size ▪ Average unit cost is subject to facility utilization ▪ Split between labour and material cost is subject to change, depending on different inflation rates for each (although material cost is usually only 5–10% of space systems' recurring cost)
Contract Type	▪ "Cost plus" contracts are tightly controlled and monitored, (firm) fixed price contracts are not, hence there is a different quality of cost information
Amortization of Non-Recurring Cost (NRC)	▪ Amortization over unit price depends on source of funding, which may be unknown ▪ NRC may be sunk or written off (see also: Infrastructure Cost)
Direct Operating Cost	▪ Propellant costs are often hidden in launch operations cost
Infrastructure Cost	▪ Infrastructure cost may be very high, but sunk, paid for since many years, with no need to recover them ▪ User fees for infrastructure as charged as part of launch price may have no relationship with the true cost, or may be not charged at all
Load Factors	▪ Specific launch cost in $/kg to a given orbit (LEO/GTO) usually assumes 100% utilization of the LV's payload capacity, this is rarely ever the case
Fixed Costs	▪ Very high fixed costs make average cost per launch highly dependable on launch rate per annum (LpA)
Subsidies	▪ Many launch vehicles are heavily subsidized by governments
Inflation	▪ Price escalation factors for the space sector are different from those of GDP deflator or Consumer Price Index (CPI) ▪ Historically, space system prices have inflated at rates between one and two times the GDP inflation rate
Accounting Rules	▪ Accounting rules may change over time, hence making extraction of category costs from project funding histories complicated
Economies of Scope	▪ Economies of scope are important issues in space policy and decision-making in the US; example: retaining a strong industrial base for solid rocket propellant production is deemed critical for US missile production

3. Measuring Space Transportation

Like every other transportation service on Earth, space transportation gets payloads from A to B by converting energy. Maybe dollars per unit of payload to orbit is not the best metric after all.

The case is made for modeling space systems based on energy metrics, like terrestrial modes of transportation

Professor Nikolai Tolyarenko
1941 –2015
International Space University

- **The original idea:** helping students at the International Space University (ISU) to compare the performance of suborbital and orbital space tourism vehicles (apples to oranges?)
- The traditional metric of payload to Low Earth Orbit (LEO) does not apply
- So, instead of looking into kg to LEO and cost per kg, the metric of additional energy (potential + kinetic) injected into 1 kg of payload was used, plus the cost per unit of energy
- **kg to orbit is replaced by Megajoules (MJ) or kilowatt-hours (kWh)**
- Using these metrics, orbital systems can easily be compared with suborbital space vehicles
- This research was mentored by the late, great Prof. Nikolai Tolyarenko

One general metric for space transportation uses Specific Orbital Energy

PRICE

Physical performance **is measured by total energy added through the launcher to its payload upon injection into orbit or trajectory.**

$$E = \frac{1}{3.6}\left(-\frac{\mu}{2a} + \frac{\mu}{R}\right) m_{Payload} \ \ [kWh]$$

- E : additional energy to payload at injection
- μ : Earth gravitational parameter [km^3/s^2]
- a : major semi-axis of orbit [km]
- R : Earth radius [km]
- $m_{Payload}$: payload mass [kg]

Economic performance **is measured by price or cost per unit of energy output in $/kWh; all amounts of money were normalized as *constant 2010 dollars.***

$$PpE = \frac{PpF}{E} \ \ [\$/kWh]$$

- PpE : price per unit of energy
- PpF : price per flight i.e. launch price [$]
- E : additional energy to payload at injection [kWh]

Using these metrics, orbital systems can easily be compared with suborbital vehicles or those from other sectors of terrestrial transportation (air, rail, road, water).

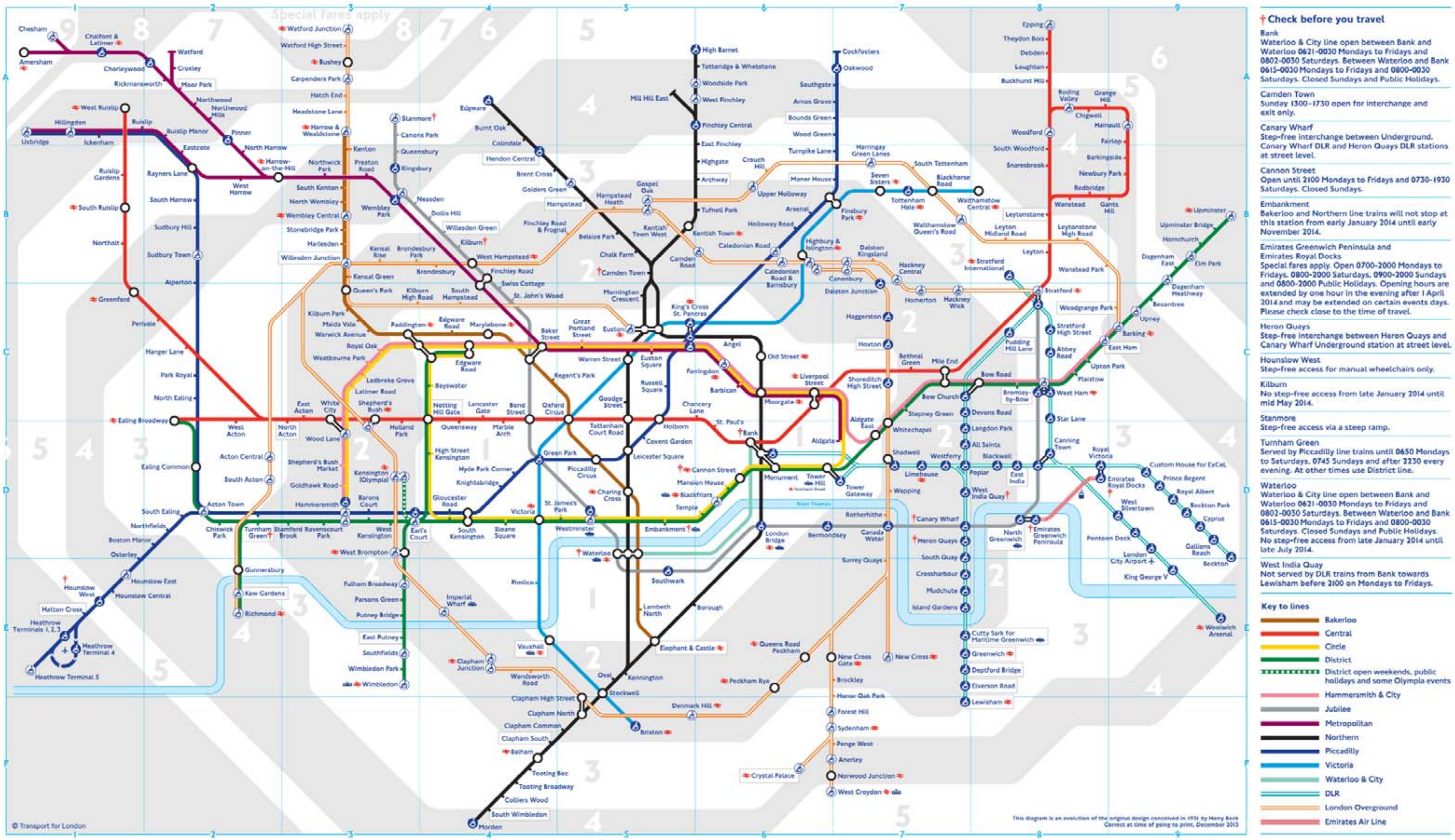
Energy metrics are already in use as price and performance indicators here on Earth

Mode		Primary Energy	Price per kWh
Cargo Transport		**MJ/TONkm**	**$/kWh**
Road	Truck and Trailer	0.5–1.9	≥0.14
Rail	Freight Train	0.34–0.6	≥0.28
Water	River Barge	0.14–0.5	≥0.16
Water	Container Ship*	0.075–0.15	0.015–0.05
Air	Aircraft	5–15	0.15–1.15
Passenger Transport		**MJ/PAXkm**	**$/kWh**
Road	Automobile	0.5–2.0	0.50–0.80
Road	Urban Bus	0.5–1.1	0.40–1.00
Road	Overland Bus	0.16–0.46	0.25–0.50
Rail	Commuter Train	1.1–1.5	0.30–1.00
Rail	Long-Distance Train	0.27–0.87	0.50–0.70
Air	Aircraft	0.95–1.9	0.20–2.00
Benchmarks		**MJ/kg**	**$/kWh**
Air/Space	SpaceShipTwo, Suborbital Mission	≈1.0**	≥6700
Ordnance	Rifle Cartridge (.470 Nitro Express)	0.205	9500
Utility	Home Electricity	n/a	0.10–0.20

Source: Umweltbundesamt, Forschungszentrum Karlsruhe, Wasser- und Schifffahrtsverwaltung des Bundes, PRICE Research, $ values for 2010 economic base year; 1 kWh = 3600 kWs = 3.6 MJ

*) Ship Size 4500–15000 TEU (Twenty-Foot Equivalent Unit) **) Energy output, not input

Tube map – it is a good metaphor: What about tariff zones for flying to space?



MAYOR OF LONDON

tfl.gov.uk

24 hour travel information
0343 222 1234*

Sign up for email updates
tfl.gov.uk/emailupdates

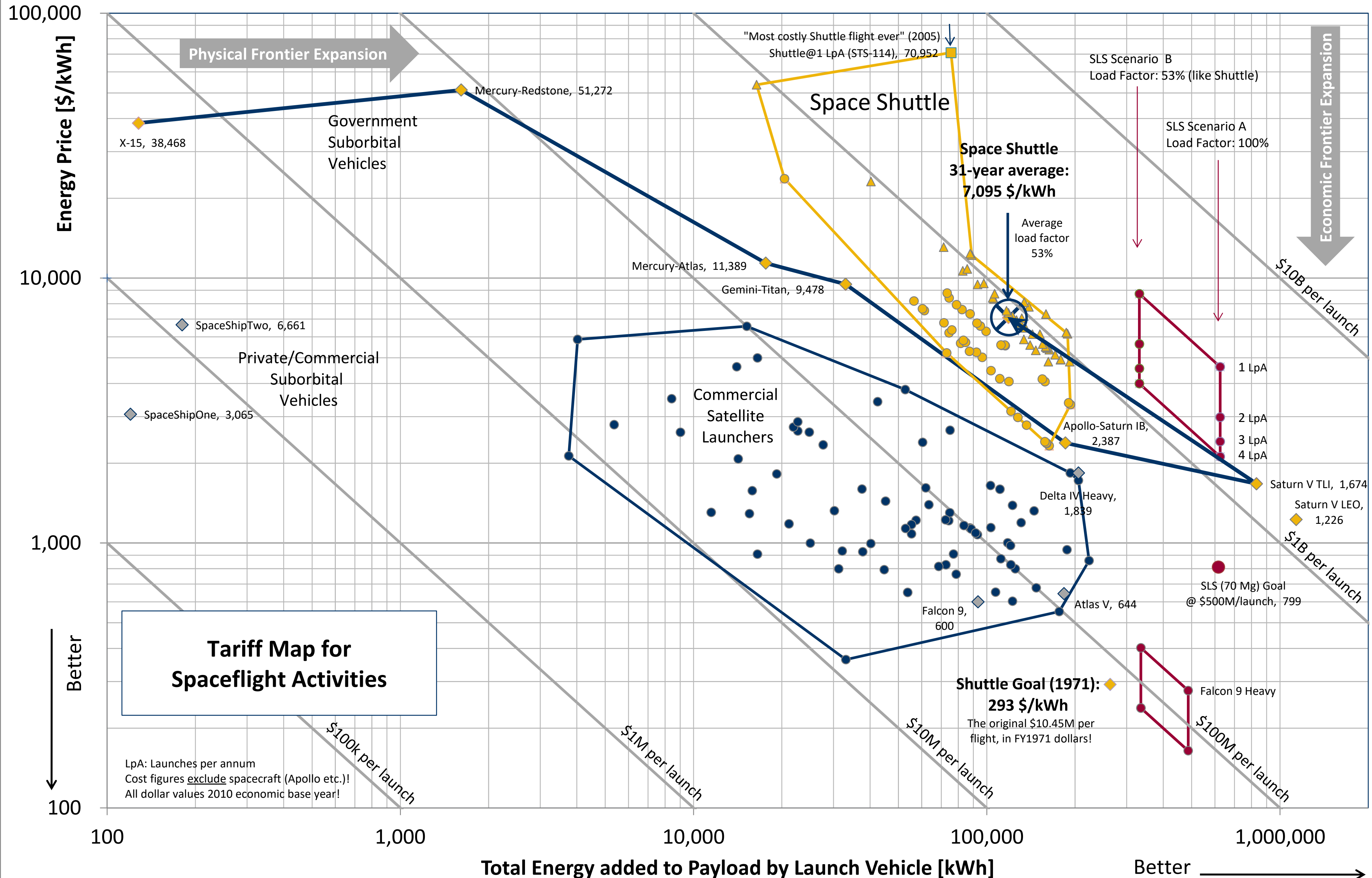
@TfLTravelAlerts

*Service and network charges may apply. See tfl.gov.uk/terms for details.

UNDERGROUND

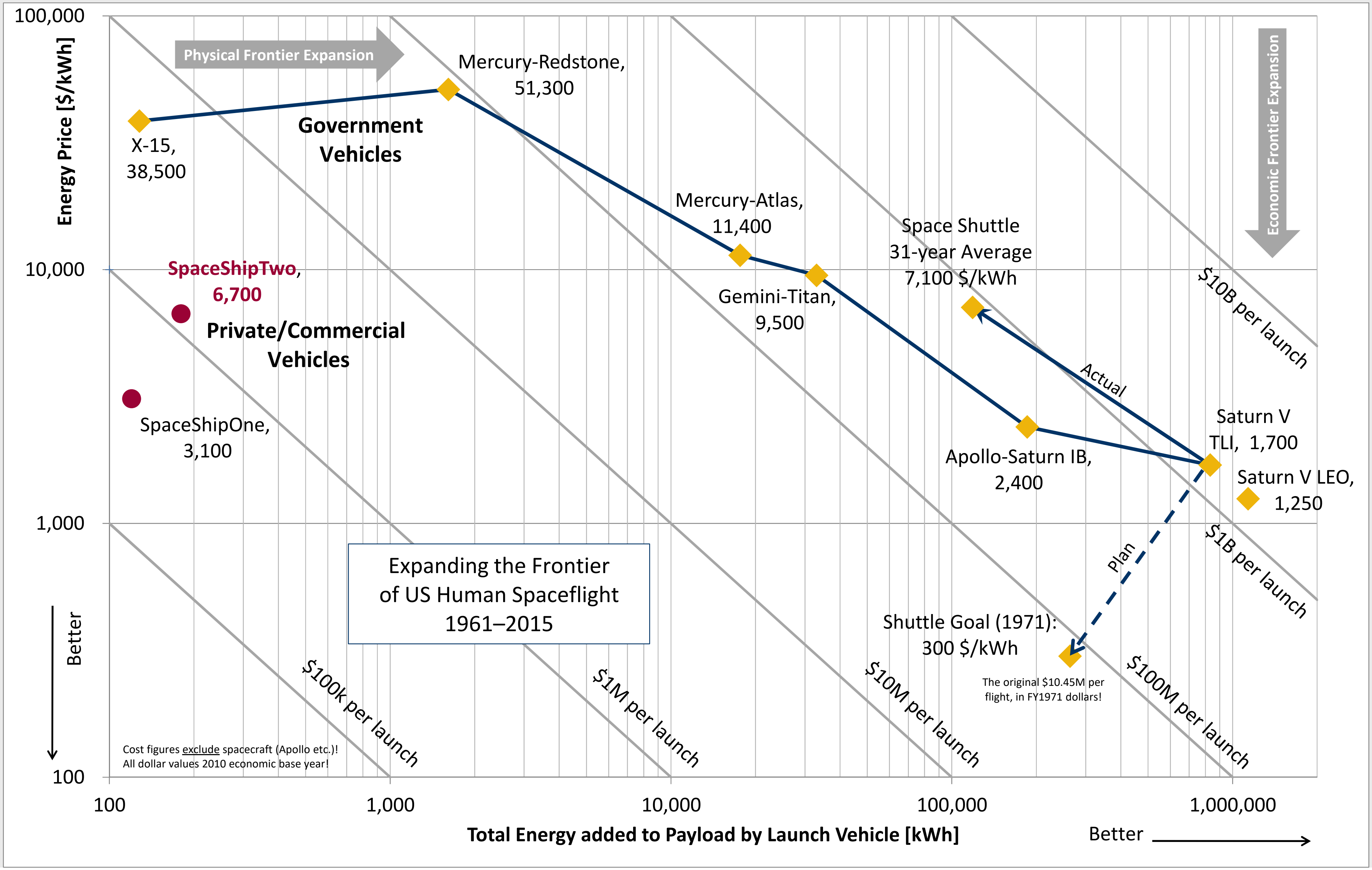
TRANSPORT FOR LONDON
EVERY JOURNEY MATTERS

Some distinct "tariff zones" for spaceflight can be identified

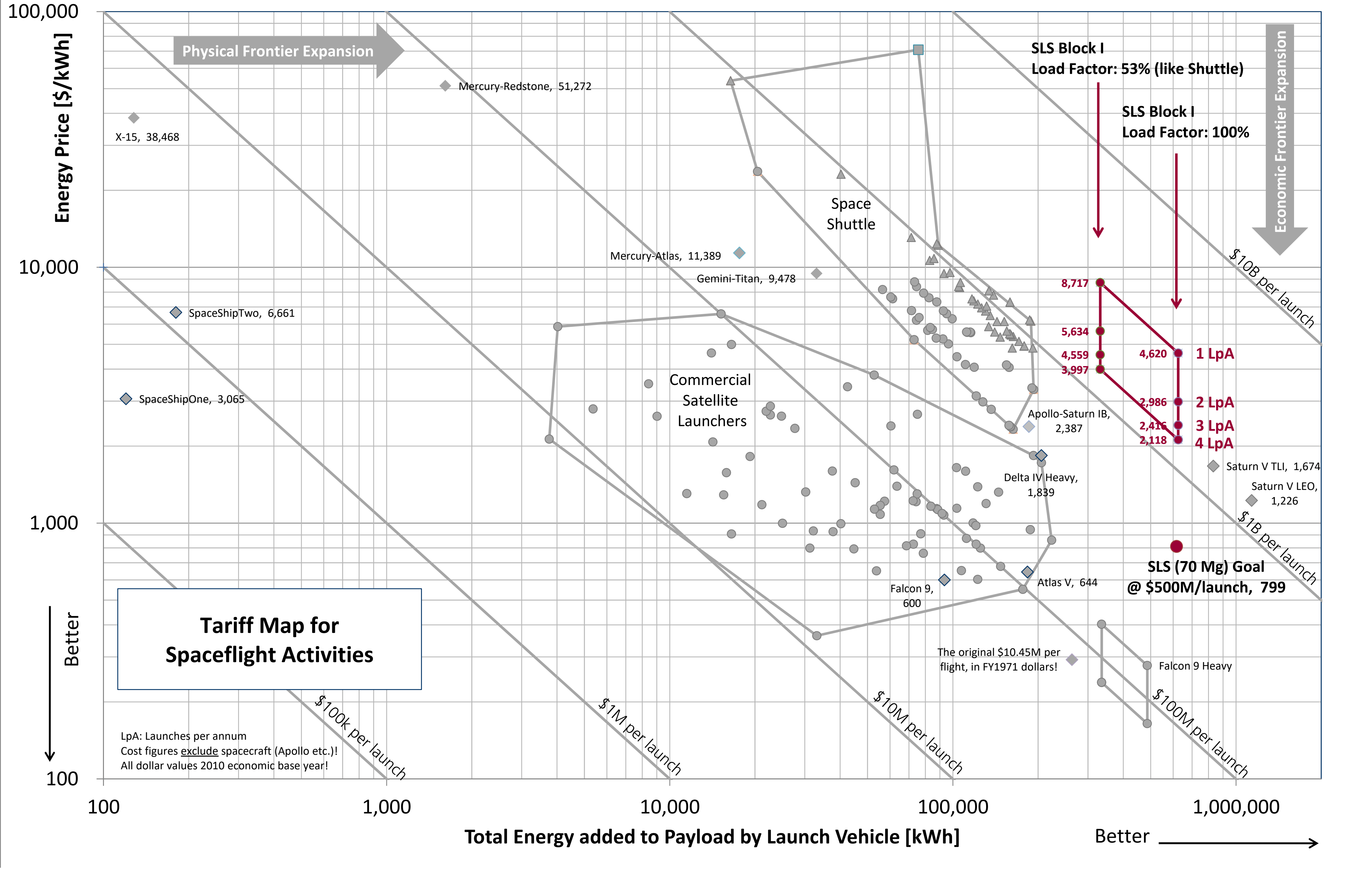


Case #1: Are we making progress at all?
At a ticket price of $200k, Virgin Galactic's SpaceShipTwo price per unit of energy is close to the Space Shuttle's 31-year average!

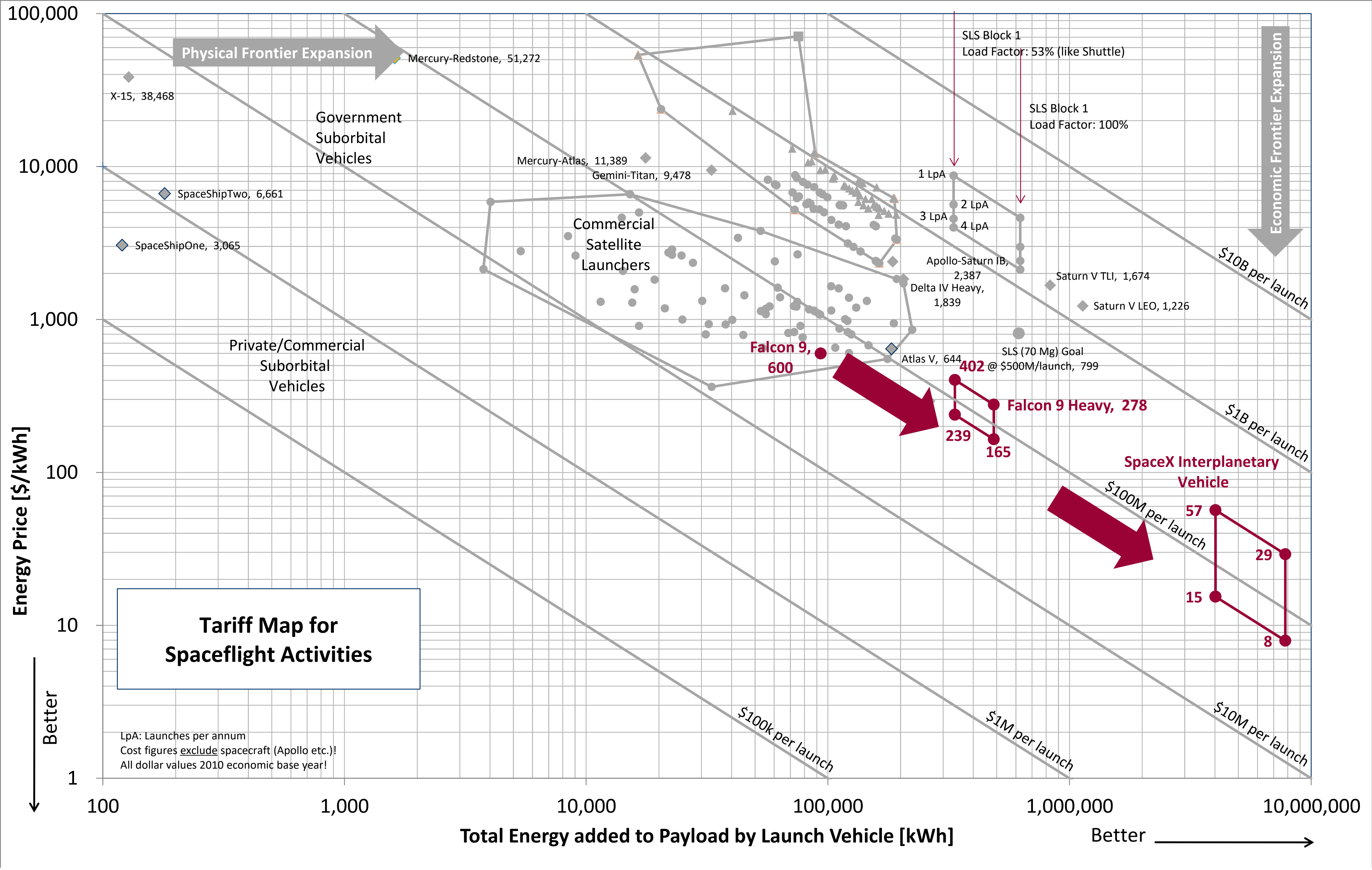
PRICE



Case #2: How will the SLS break free from its Shuttle legacy?



Case #3: SPACEX's proposed Interplanetary Spaceship expands the Frontier, but will gigantism work this time?



The lessons learnt so far are a good starting point for future study activities

PRICE

1. Commercial Launch Offerings

- The commercial launch market, not yet selling crew-rated launchers, offers pricing between 360 $/kWh and 6600 $/kWh
- Suborbital space tourism has the same high specific costs of the Space Shuttle: SpaceShipTwo costs between 6700 $/kWh and 8300 $/kWh, depending on ticket price ($200k vs. $250k)

2. The Space Shuttle Legacy

- Original 1971 goal of <300 $/kWh was missed: >7000 $/kWh (134-flight average)
- The proposed Space Launch System (sls), Block 1, if it achieved $500M per launch, would extrapolate the Shuttle's 8 launches-per-year trend line: at 800 $/kWh
- Yet, assuming similar high fixed costs and low launch rates of 1–2 /year, a much higher cost per launch can be foreseen

3. The Future of Heavy Lift

- The upcoming SPACEX Falcon 9 Heavy promises to achieve the Shuttle's original goal of <300 $/kWh!
- The SPACEX 100+ passenger Interplanetary Spaceship promises $140 per kg to Mars, equaling 8 $/kWh; 3 orders of magnitude lower than the Space Shuttle and close to terrestrial air travel! Too good to be true?

4. Economics of Space Transportation

- The economics needed for meaningful human exploration beyond LEO, below the Shuttle's original 300 $/kWh goal, haven't come from SSTO
- Yet, significant reductions are promised, based on streamlined manufacturing combined with full reusability, in-situ propellant production (methane fuel) and refilling in orbit
- "This time it's different." Is it?

PRICE

Backup Slides

***

Energy is a good metric for space transportation: A mass brought to, say, orbital velocity shows a significant energy increase

PRICE

1kg in Low Earth Orbit

Altitude = 185 km

Velocity = 7,797 m/s

Specific Orbital Energy = -30.43 MJ/kg

1kg resting on ground on Earth's equator

Altitude = 0 km

Velocity = 465.1 m/s (Earth rotation)

Specific Orbital Energy = -62.6 MJ/kg

In the end, a space transportation customer buys ENERGY.