# DARPA 10-Year Lunar Architecture (LunA-10) Capability Study: Lunar Rail Network Infrastructure Study

## LSIC Overview

This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA).

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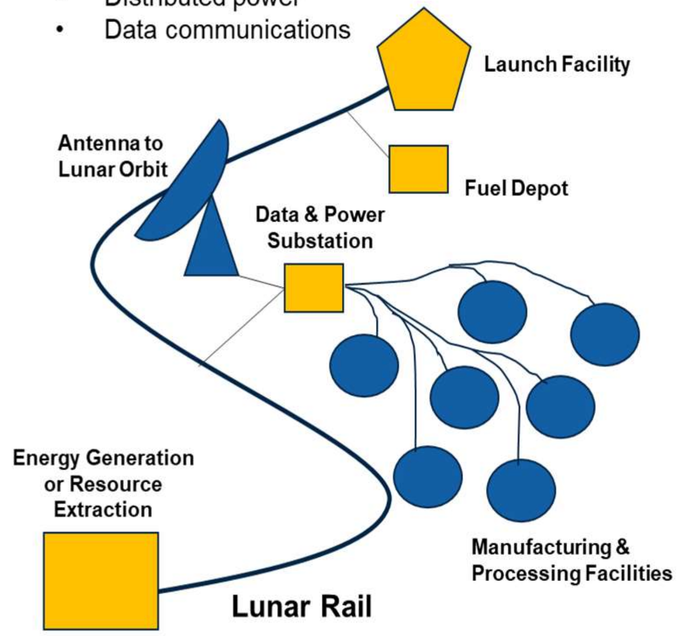
25 April 2024

# Lunar Rail Network: Project Introduction

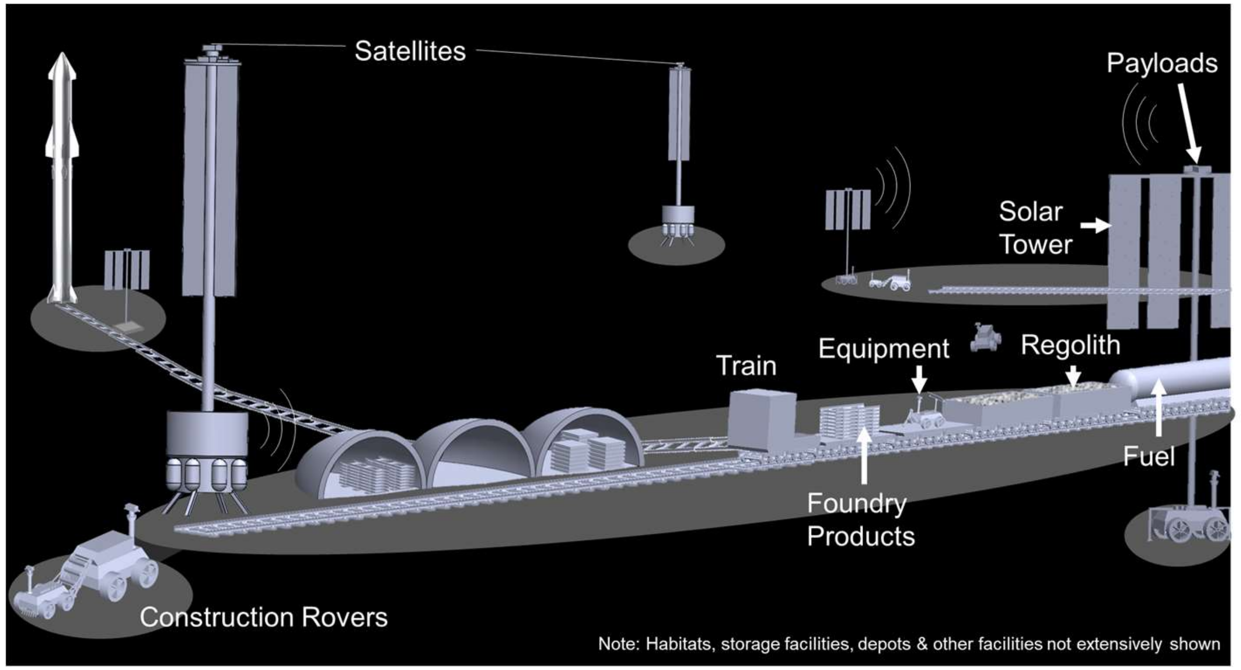
- **Challenges with Rovers:**
  - Dust, Range, Payload Capacity, Speed, Rolling Resistance, Surface Wear, Recurring Cost
- **Potential Solution: Could we build a rail network on the Moon? Should We?**
  - Move large amounts of mass easily and efficiently with minimal impact to surface

**Launch Site Needs:**

- Propellant delivered to storage depot
- Distributed power
- Data communications

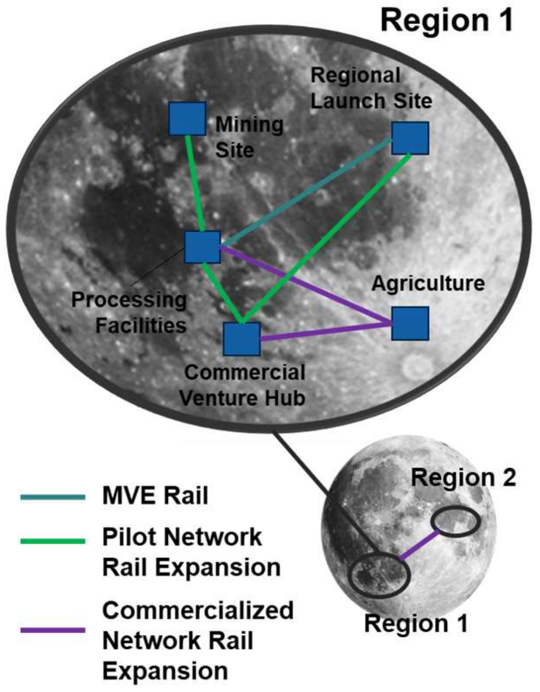


Source: Northrop Grumman Lunar Rail Network Study



Note: Habitats, storage facilities, depots & other facilities not extensively shown

Source: Northrop Grumman Lunar Rail Network Study



Notes: Destinations are for illustration only; Not to scale.

Source: Northrop Grumman Lunar Rail Network Study

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# LunA-10 & Lunar Rail Mission Space

## Mission A:
## Surface Transport of Lunar-Derived Materials for Cislunar and Earth Orbit ISAM

1) Cost for Space Launch to Low Earth Orbit- Aerospace Security Project (csis.org)

2) Commercial Lunar Propellant Architecture: A Collaborative Study of Lunar Propellant Production (isruinfo.com)

**Projected Value:**
*(Assuming Starship lowers price of $1500/kg to LEO[1] to $300-$600/kg)*

~$1,400-$2,600/kg to GEO (4x LEO[2])
~$2,000-$3,800/kg to Moon (>6x LEO[2])

**Demand:**
- Fuel for Deep Space: 100MT/trip
- Refueling in GEO: 300MT+
- Projected Construction: 100MT's

**Projected Annual Market Value:**
- 500MT-2500MT = $1.6B-$8B

## Mission B:
## Surface Resource Mobility for Lunar Surface Scientific Missions

**Missions:** Lunar Telescopes, Solar Weather Monitoring, Biological Understanding, etc…

**Demand:** Multiple per decade (10's to <200)
**Mission Value:** Cost avoidance of bringing power, comm, rovers and equipment. ~10,000 kg per mission = $38M launch cost plus $100M+for the equipment → $150M per mission

**Projected Annual Market Value:**
- $0.5B-$3B

## Mission C1:
## Lunar Surface Tourism

**Demand:** Driven by price
**Price:** Per one study, ~$75M per ticket[3] for a tour that includes surface mobility and 20 passengers (price may come down, and buyers would grow)

**Projected Annual Market Value:**
- $0B to $1.5B

## Mission C2:
## Goods from/to Earth

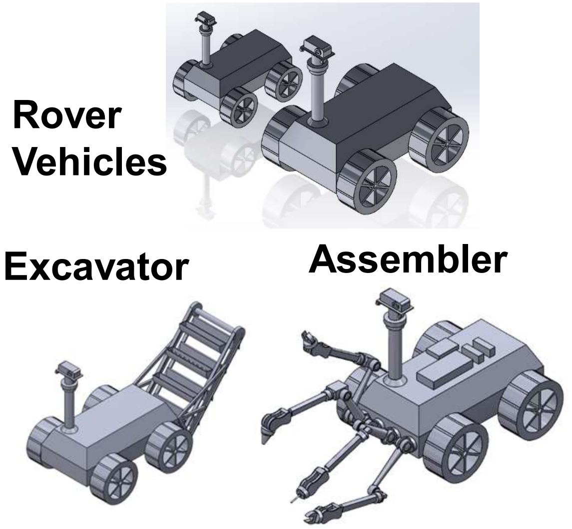
**Potential Demand/Value:**
- Moon Souvenirs/Burials ($20M) [3]
- Other: <$20M

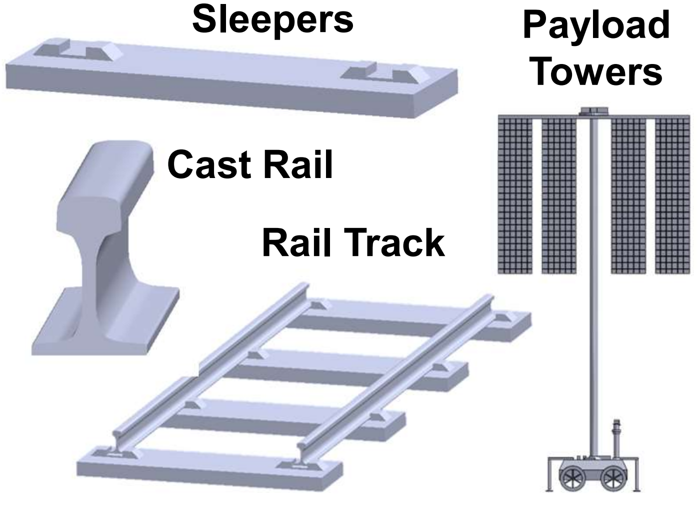
**Projected Annual Market Value**
- ~$0.05B

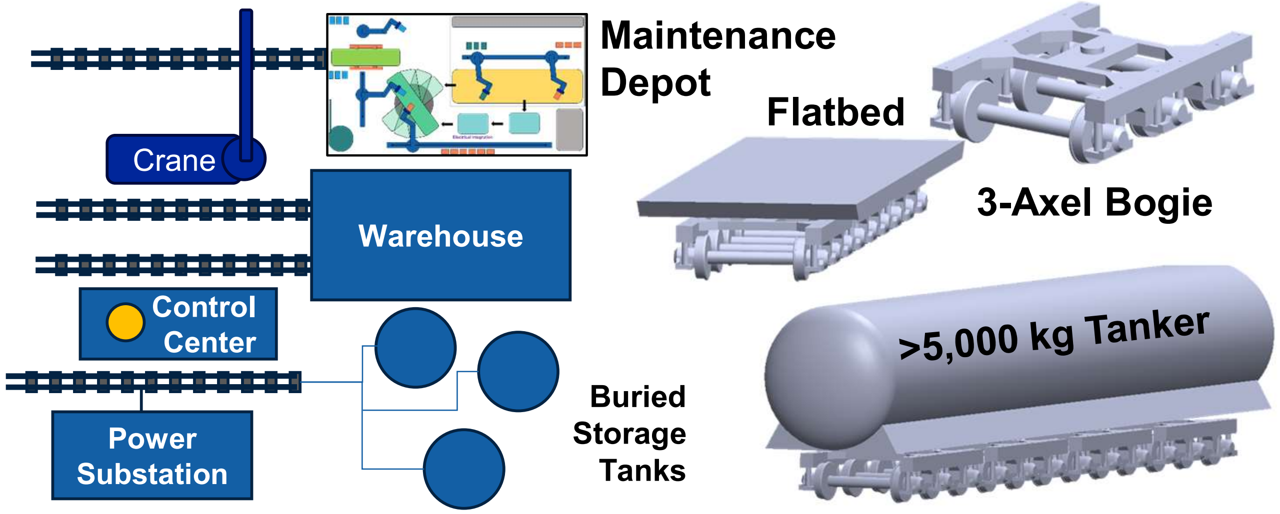
3) Demand Drivers of the Lunar and Cislunar Economy (newspaceeconomy.ca)

**Large mass transport may be key to $2B to $13B of annual economic activity by 2035**

# Lunar Rail Network Product Overview







## Construction & Maintenance Equipment

- **Construction Rover Vehicles**
  - Med (500kg), Heavy (2500kg)
- **Construction Payloads**
  - Survey, Excavate, Haul, Doze/Compact, Assemble, Supervise, Crane
- **Inspection & Maintenance Payloads**
  - Wear Monitoring, Weld Repair, Component Replace

## Rail Route Infrastructure

- **Embankments**
- **Bridges**
- **Integrated Rail Track**
  - Sleepers, Rails, Fastening System, Switches
- **Additional Service Infrastructure**
  - Comm/Power/PNT Payload Towers
  - Wired Grid
  - Pipelines

## Rail Station Infrastructure

- **Comm/Power/PNT Payload Towers**
- **Command and Control**
  - Control Electronics, Sensors, Data Management/Analytics
- **Traffic & Payload Management**
  - Switches, Loading Docks, Maintenance Depot
- **Resource Distribution Infrastructure**
  - Substations, Data Centers, Storage Tanks, Warehouses

## Integrated Rail Vehicles

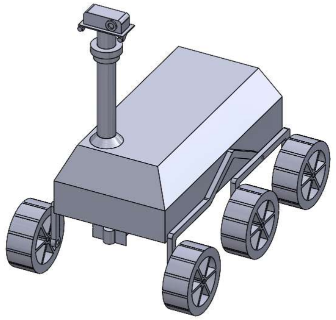
- **Rail Vehicle Platform**
  - Couplers, Bogie Attachments, Primary Frame
- **Engine Electronics Bus**
  - Power, Communications, Control, Radiators
- **Payload Transport Assemblies (Tankers, Hoppers, Flatbeds)**
  - Payload Structures, Electrical Control Boxes
- **Bogies**
  - Motors, Brakes, Wheel Sets, Frames, Suspensions

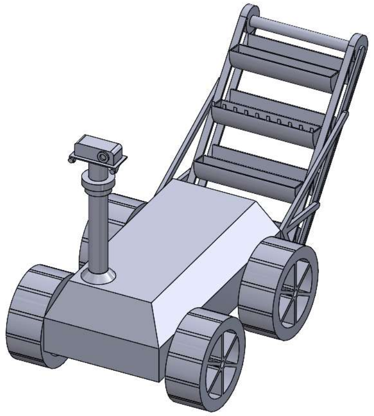
Source (All): Northrop Grumman Lunar Rail Network Study

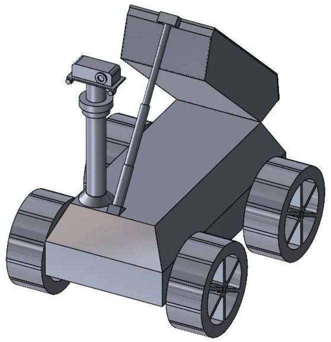
# Foundation Forming Equipment Concepts

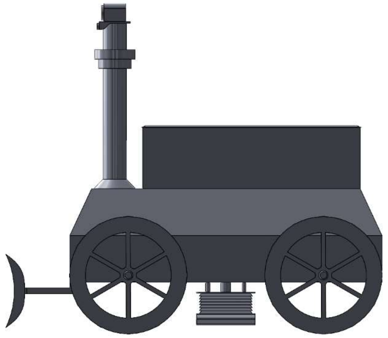
- **Surveyor (S):** High-mobility platform with ground penetrating radar and regolith characterization
- **Excavator (E):** Base platform with articulated bucket ladder for excavation with rippers along chain
- **Hauler (H):** Base platform with coverable bin
- **Compactor (C):** Base platform with a vibratory plate compactor, an articulated vibratory dozer for large rocks and coarse/fine grading, and a coverable bin
- **Assembler (A):** Base platform with robotic arms with for placing, sintering, and welding
- **Manager (M):** Base platform with outriggers, solar arrays, and communications/PNT

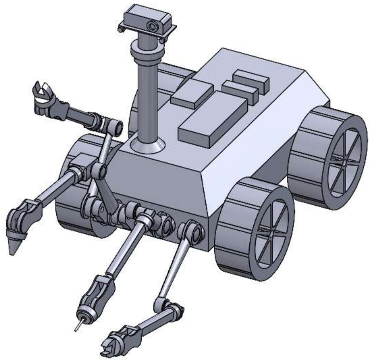
| Type | Approx. Duty Cycle | Notional Unit Launch Mass (kg) | Notional Unit Average Power (kW) |
|---|---|---|---|
| Surveyor | 90% | 500 | 0.5 |
| Excavator | 70% | 1,300 | 2.3 |
| Hauler | 70% | 1,400 | 1.0 |
| Compactor | 90% | 1,500 | 0.5 |
| Assembler | 70% | 1,100 | 2.1 |
| Manager | 100% | 1,000 | 0.1 |


Surveyor


Excavator


Hauler

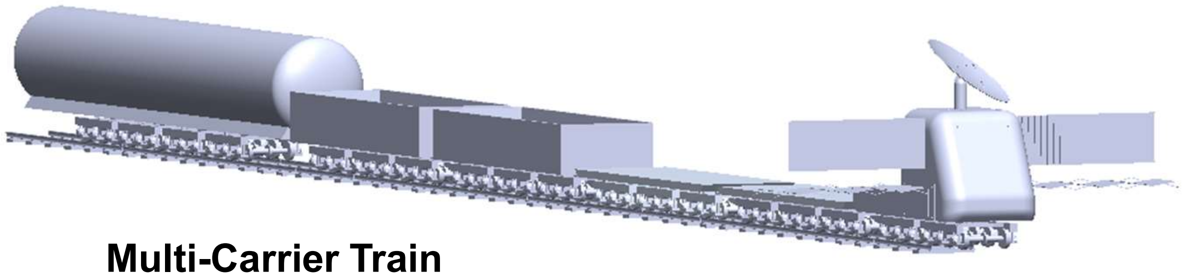

Compactor


Assembler

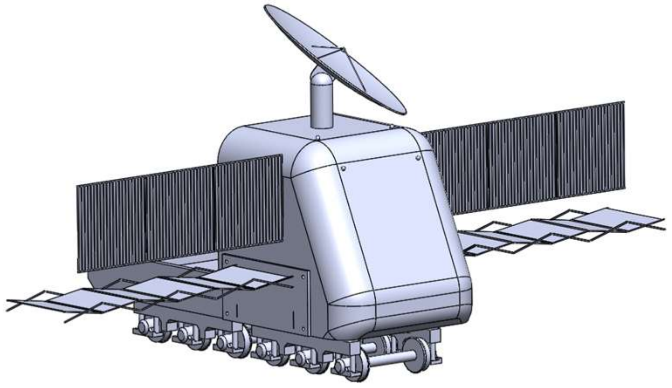

Manager

Source (All): Northrop Grumman Lunar Rail Network Study

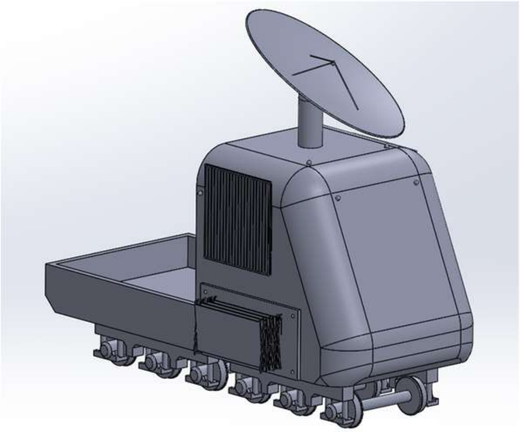
# Rail Network Design & Analysis



**Multi-Carrier Train**



**Lunar Day Configuration**

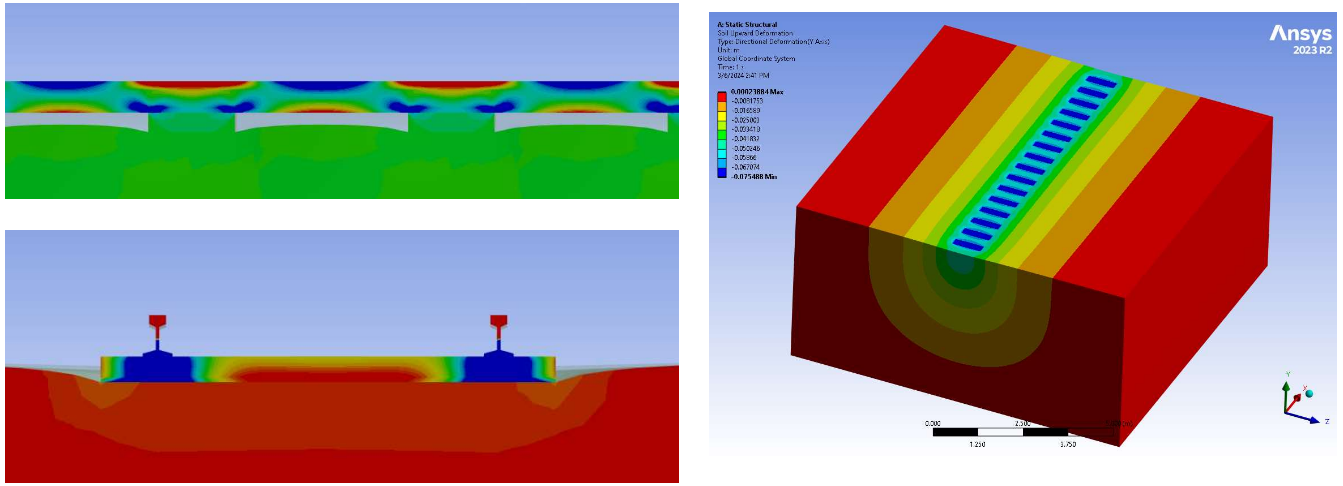


**Lunar Night Configuration**

Train and carrier concept designed with modularity:
- Minimizes launched mass of equipment
- Bogies, frames & transport assembly concepts are reconfigurable to payload transport needs

**Key Design Challenges:**

- **Lunar Soil:** Uncertainty in lunar soil modulus of elasticity for compacted regolith → Potential for deflections >5 cm even with well distributed loads
- **Energy:** High energy consumption for sintering regolith or extracting and processing metals → Drives goal to minimize processed material for architecture
- **Gravity:** Reduced gravity vector → reduces traction force and either increases required cant angle in turns or limits speeds in turns



**Lunar Soil Deformation**

Source (All): Northrop Grumman Lunar Rail Network Study

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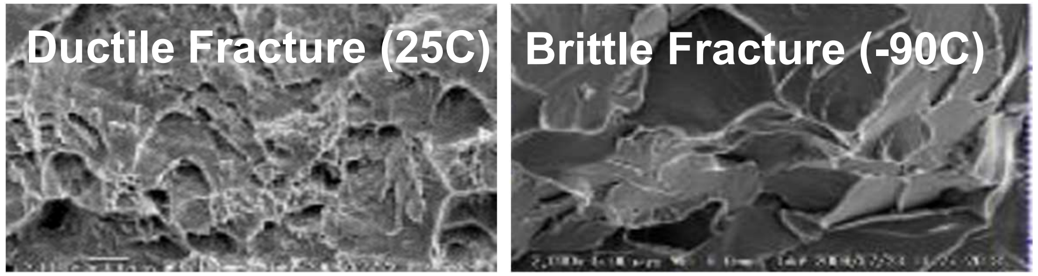
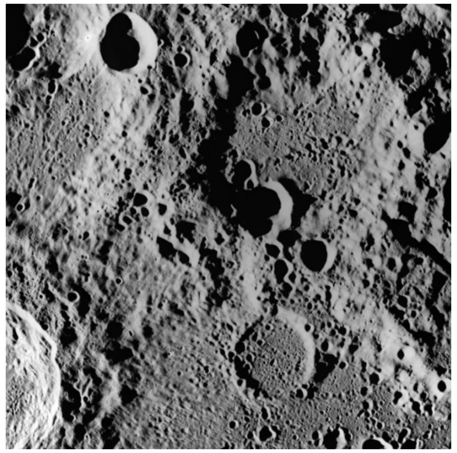
# Lunar Rail Materials Challenges

- **Limited In-Situ resource availability**
  - Metal extraction from regolith is challenging
  - Producible alloys differ from common Terrestrial options
- **Extreme temperatures (<-200C to >120C)**
  - Raises concerns for ductile to brittle transitions, thermal expansion, and over-aging
- **Vacuum environment**
  - Lack of surface oxide accelerates wear and cold welding
- **High stress between the wheel and rail**

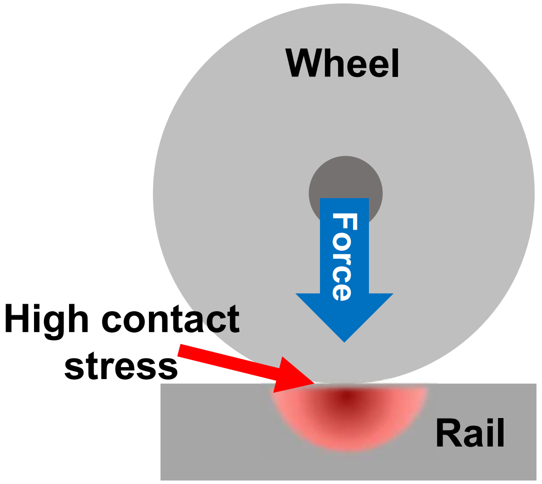


Source: Ductile-to-Brittle Transition and Brittle Fracture Stress of Ultrafine-Grained Low-Carbon Steel - PMC (nih.gov)

**Lunar surface**

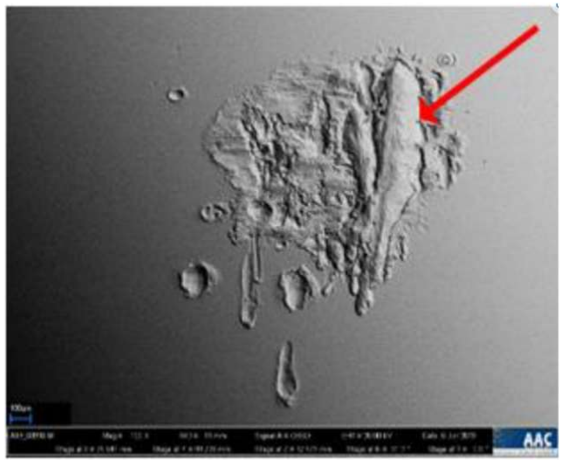


Source: Apollo Image Archive (asu.edu)



Source: Northrop Grumman Lunar Rail Network Study

**Wear Examples**



Source: Cold Welding in Space Mechanisms Due to Fretting (mdpi.com)

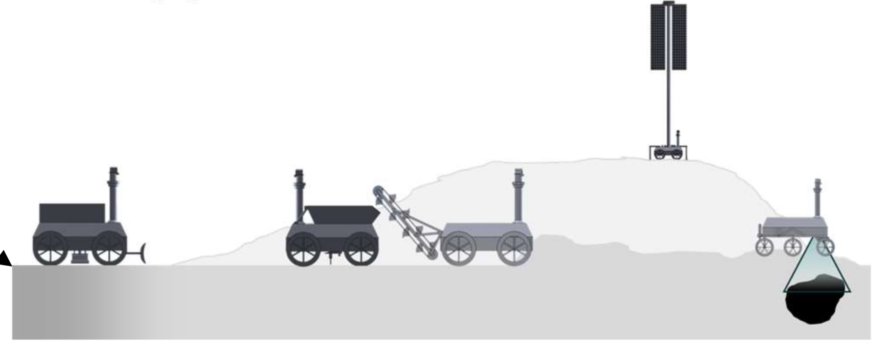
**These challenges significantly constrain material selection options**

# Minimum Viable Experiment (MVE) Phase 1 Objectives

- Goals: Demonstrate commercial ISRU resource extraction framework viability:

| | | | |
|---|---|---|---|
| Perform Mining, ISRU & Foundry Operations | Perform Minimum Viable Lunar Surface Infrastructure Construction | Perform Minimum Viable Rail Transport | Execute First Commercial Sale of Lunar Fuel |

- **MVE Operations Equipment:** 2 Flatbeds (1 Motorized) + 1 Hopper Carrier
- **Potential MVE Phase 1 Lunar Rail Activities:**
  - Site preparation (surveying, excavating & compacting)
  - Load hopper with regolith during route construction (demo regolith loading/delivery), deliver regolith to ISRU station & resource processing payloads
  - Load engine/flatbed #1 with finished foundry and cast products and deliver to construction fleet (demo goods delivery)
  - Use produced rails & sleepers in construction of rail network length
  - Install power nodes, demonstrate secondary services
  - Place tank on flatbed #2, transport fuel (demo tanker transport) and launch
    - Would bring or harvest a spent propellant tank
    - May need a small propellant tug with launch system to return fuel to orbit



**NOTE:** Performing these activities is not in scope of the LunA-10 study

Source (All): Northrop Grumman Lunar Rail Network Study

# MVE to Pilot to Operational Expansion

- **Minimum Viable Experiments (MVE):** Prove Lunar surface viability and refines architecture design
- **Pilot Expansion:** Uses second generation carriers/engines & construction equipment (same track gauge)
- **Operational Rail Network:** Settlement 1 infrastructure complete, fully operational and generating revenue

**Initial Development**

↓

**MVE & Architecture Refinement**

↓

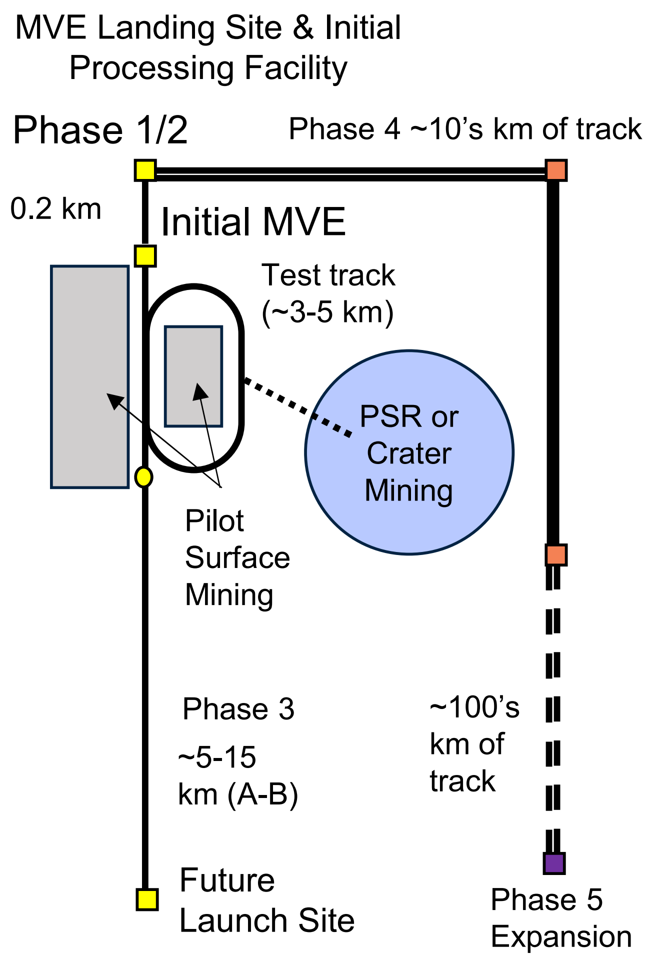
**Pilot Expansion**

↓

**Operational Rail Network**

| Years | Development Phase | Phase Activities* |
|---|---|---|
| 2 | Scientific Understanding | Gap mitigation & fundamental science |
| 2 | MVE Development | Non-Recurring Engineering, Manufacturing, Assembly, Equipment Testing & Demos |
| 1 | MVE Integration, Test & Launch/Transit | Integration, test, launch & transit to Lunar surface |
| 1 | Phase 1 MVE | Construct rail of ~0.2 km, perform MVE Phase 1 Demo |
| 2 | Phase 2 MVE | Add dynamics, civil engineering & wear test track to mature railroad architecture. Support early mining & foundry. |
| 1 | Phase 3 Pilot | Expand to connect to high traffic launch site |
| 1 | Phase 4 Pilot | Add additional routes to other processing facilities around 1st settlement, scale towards full operational state |
| 3+ | Phase 5 Operational Expansion | Expand reach to additional settlements (investments justified for each addition) |

## Concept of Expansion



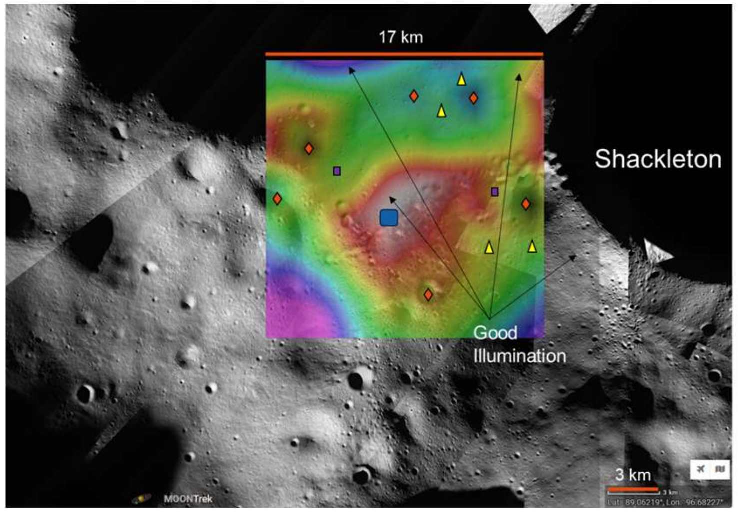
**Lunar Rail Network would Scale as Lunar Surface Utilization Grows**

***NOTE:** Performing these activities is not in scope of the LunA-10 study

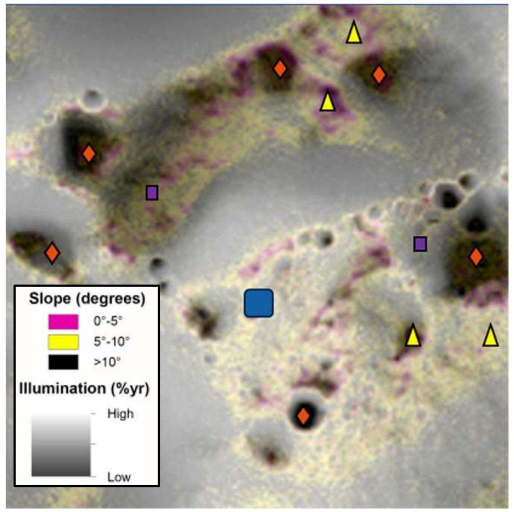
Source (All): Northrop Grumman Lunar Rail Network Study

# MVE Site Selection & Expansion

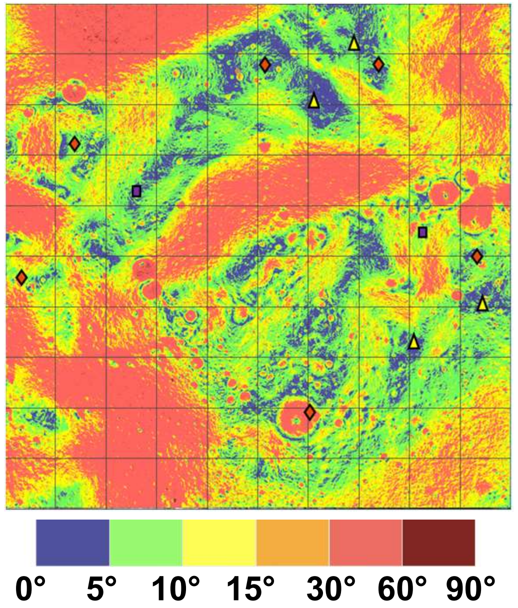
**Elevation and Regional Context**[1]



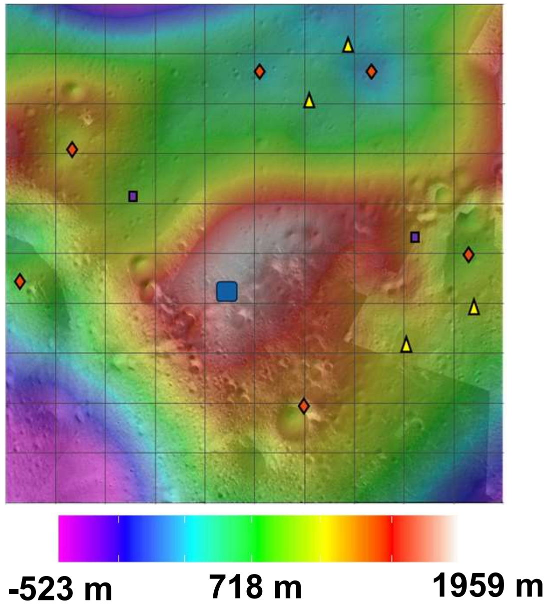
**Illumination & Slope**[2]



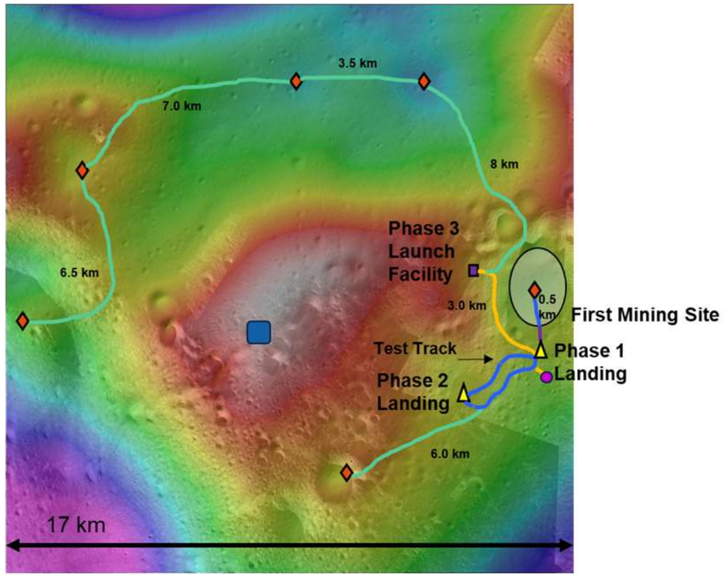
**Slope Angle**[1]



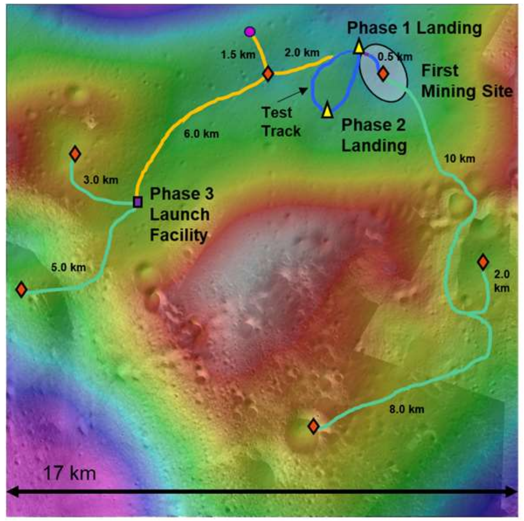
**Elevation**[1]



## Lunar Rail Network Study: Design Reference Plan 1



## Lunar Rail Network Study: Design Reference Plan 2



◆ **Permanently Shadowed Regions (Mining Resources)**

△ **Candidates for Phase 1/2 MVE Landing**

■ **Candidates for Phase 3 Launch Facility**

■ **Artemis Site 001**

**Plan 1**

- **Phase 1: 0.2 km**
- **Phase 2: 4.0 km**
- **Phase 3: 4.5 km**
- **Phase 4: 31 km**

**Plan 2**

- **Phase 1: 0.2 km**
- **Phase 2: 4.0 km**
- **Phase 3: 9.5 km**
- **Phase 4: 28 km**

**Phase 5:**
**~300-400 km**
**(not shown)**

Sources:
(Adapted from)

1) Barker, M.K., et al. (2020), Improved LOLA Elevation Maps for South Pole Landing Sites: Error Estimates and Their Impact on Illumination Conditions, Planetary & Space Science, in press, doi:10.1016/j.pss.2020.105119.
2) Stopar J. and Meyer H. (2019) Annual Illumination and Topographic Slope of the Moon's South Polar Ridge, Lunar and Planetary Institute Regional Planetary Image Facility, LPI Contribution 2179, https://repository.hou.usra.edu/handle/20.500.11753/1264

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# Investment & Trip Price by Phase Summary

## Non-Recurring Engineering & Operations

- Concept Development and Design of Infrastructure and Transport System
    - Train, Civil Structures, Substations, Construction Equipment
- Launch of material to Moon Base
- Test track and equipment/system maturation
- Lunar Rail staged infrastructure buildup
- Manufacturing, integration, test and launch of construction equipment and Earth-sourced components/assemblies

## Recurring Engineering & Operations

- Operational cost of train (energy, comms/PNT, loading/unloading)
- ISRU-derived manufacturing of new elements and maintenance of existing elements (Railcars, beds, etc.)

Source: Northrop Grumman Lunar Rail Network Study

| Parameter | Phase 1 | Phase 2 | Phase 3 | Phase 4 | Phase 5 |
|---|---|---|---|---|---|
| Average Trip Length [km] | 0.2 | 2.4 | 3.9 | 24 | 128 |
| Average Trip Payload [kg] | 200 | 5,000 | 32,000 | 45,000 | 83,000 |
| Total Launched Mass by Phase [kg] | 16,100 | 25,300 | 64,200 | 90,000 | 167,000 |
| ISRU Metallic Mass Required [kg] | 1,800 | 43,300 | 212,000 | 520,000 | 3,700,000 |
| **TOTAL Estimated NRE [$B]** | **0.5-1.0** | **0.5-1.0** | **2.0-3.0** | **2.0-3.0** | **4.0-5.0** |
| **TOTAL Estimated RE [$B]** | **---** | **<0.1** | **0.1-0.2** | **0.3-0.5** | **2.0-3.0** |
| **TOTAL Goal Avg Price per Trip [$M]** | **N/A** | **8.0** | **8.0** | **5.0** | **2.5** |
| **Mass Price Efficiency [$USD / kg-km]** | **17,700,000** | **660** | **51** | **3.4** | **0.23** |

**Note:** Numbers shown are to ballpark costs and do not include contingency. At the final system concept review the numbers will be updated along with the assumptions below.

### Pilot Lunar Rail – Key Architecture Assumptions

Phase 2+ Price Per Trip: ~$2.5M-$8M

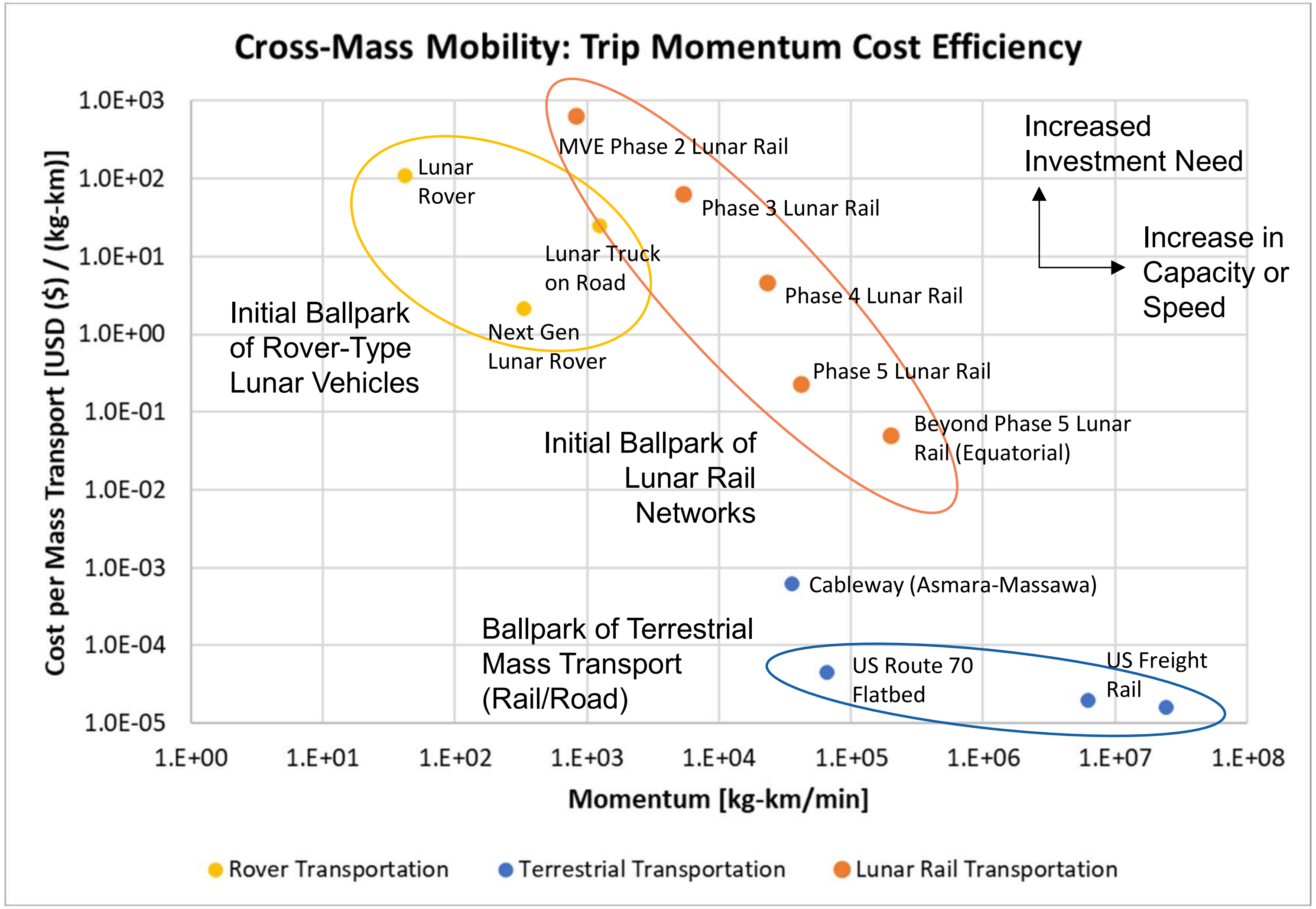
- Max Transport Mass: 100,000 kg – 125,000 kg
- Cost Assumptions:
    - Development Cost - $30,000 per kg[1] (Equipment, Detailed Components)
    - Development Cost - $3,000 per kg (Maintenance Depot Building)
    - Cost of Launch to Moon Base - $10,000 per kg (~7x Falcon 9 to LEO)[2]
    - Cost of Manufacturing Metal Parts on the Moon - $500 per kg
    - Cost of Manufacturing Equipment on Earth - $5,000 per kg
    - Cost of Energy on the Moon - $100 per kWh
    - Maintenance: 5% per year of manufacturing cost for infrastructure (20-year life), 20% per year for carriers (5-year life)

Additional Sources:
1) Demand Drivers of the Lunar and Cislunar Economy (newspaceeconomy.ca), Page 123
2) Cost for Space Launch to Low Earth Orbit- Aerospace Security Project (csis.org)

# Cross-Mass Mobility: Trip Momentum Cost Efficiency

## *White Space Plot Draft Result*

**Note:** Derivation of the terrestrial transportation and rover values will be discussed in the LunA-10 Final Report



- Initial Take-Aways:
  - Rover constrained by capacity
  - Lunar rail constrained by infrastructure cost
  - Slope is steeper with higher infrastructure cost, offset by increasing capacity of transport
  - Refinement of total costs and capacities is important to understanding rover vehicle versus rail overlap region
  - Developing projected transport service demand is important to determine when rail makes strict economic sense with all other things being equal

**Cross-Mass Mobility: Momentum Cost Efficiency**

| Transport Methodology | X Axis: kg*km/min | Y-Axis: $/kg-km |
|---|---|---|
| Lunar Rover | 42 | 109 |
| Lunar Truck on Road | 1250 | 24.7 |
| Next Gen Lunar Rover | 333 | 2.13 |
| Phase 2 Lunar Rail Transport | 830 | 656 |
| Phase 3 Lunar Rail Transport | 5400 | 63.6 |
| Phase 4 Lunar Rail Transport | 23000 | 4.65 |
| Phase 5 Lunar Rail Transport | 42000 | 0.23 |
| Beyond Phase 5 Lunar Rail Network | 200000 | 0.05 |
| Cableway (Asmara-Massawa) | 35900 | 0.000612 |
| US Route 70 Flatbed | 66000 | 0.000045 |
| US Freight Rail Transport (Long) | 24500000 | 0.000016 |
| US Freight Rail Transport (Short) | 6250000 | 0.000020 |

**There is a rover to rail cross-over point around >1000 kg-km/min and/or achieving <$5-10/kg-km**

Source (All): Northrop Grumman Lunar Rail Network Study

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