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

LSIC Overview

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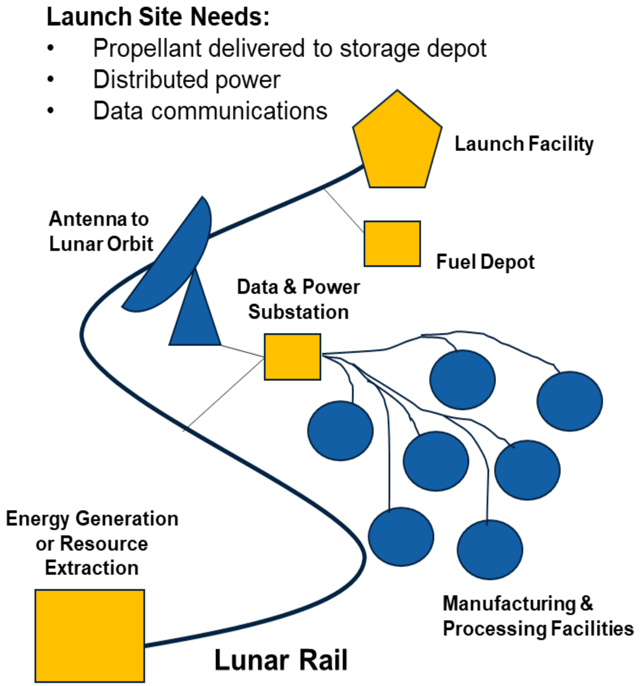
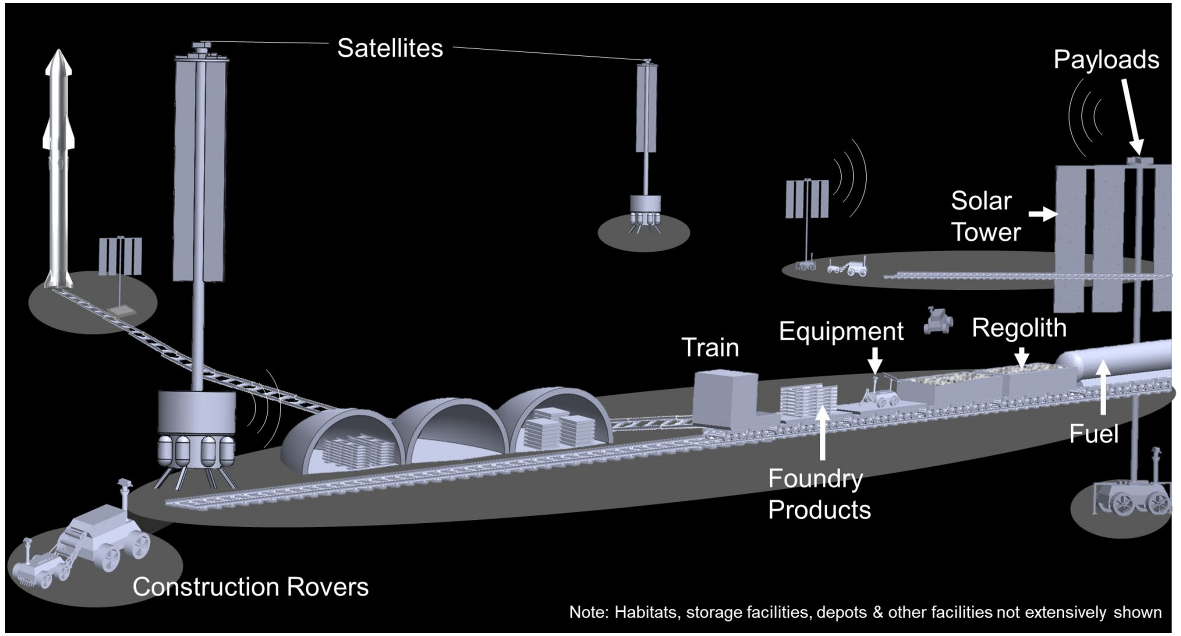
25 April 2024

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



Source: Northrop Grumman Lunar Rail Network Study



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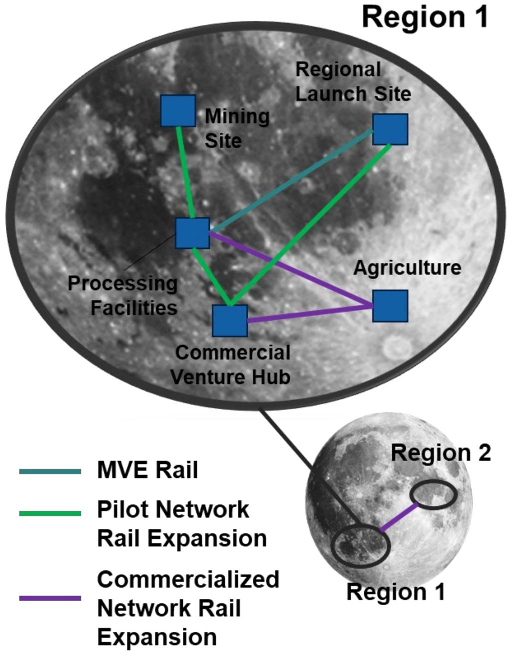


Notes: Destinations are for illustration only; Not to scale.

Source: Northrop Grumman Lunar Rail Network Study

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

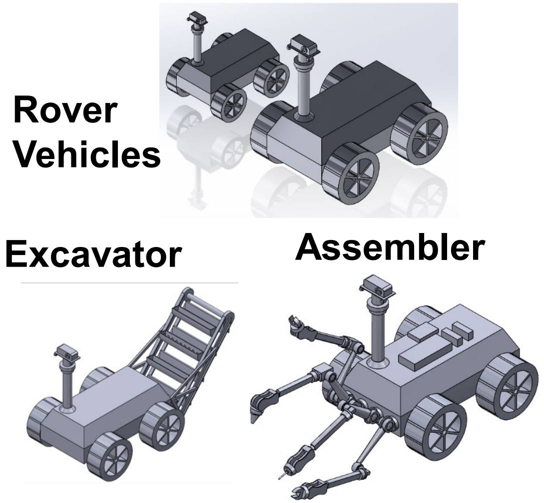
Potential Demand/Value:
- Moon Souvenirs/Burials ($20M)[3]
- Other: <$20M

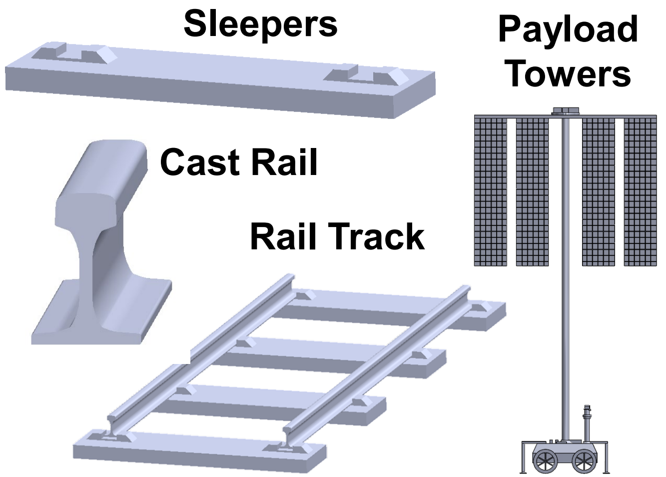
Projected Annual Market Value
- ~$0.05B

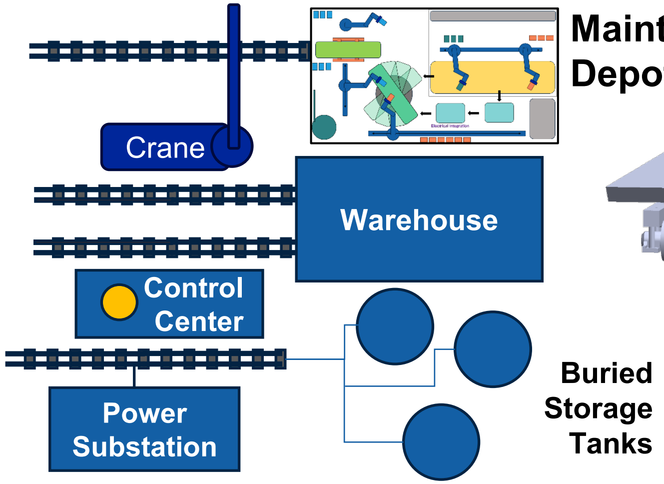
3) Demand Drivers of the Lunar and Cislunar Economy (newspaceeconomy.ca)

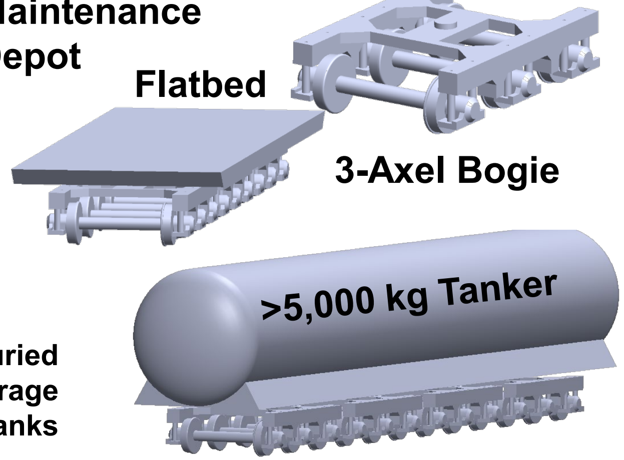
Large mass transport may be key to $2B to $13B of annual economic activity by 2035

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

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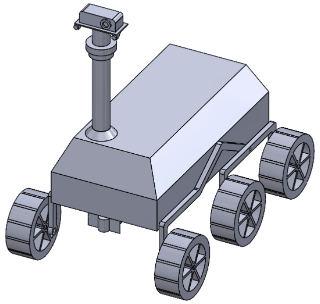
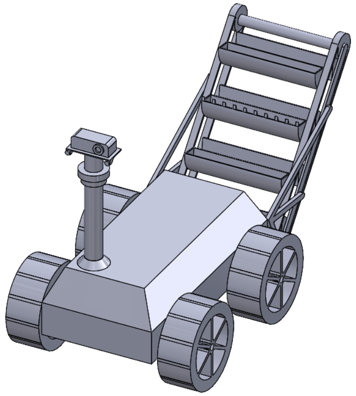
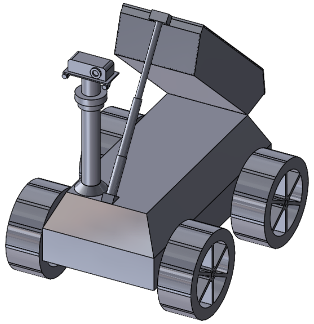
Foundation Forming Equipment Concepts

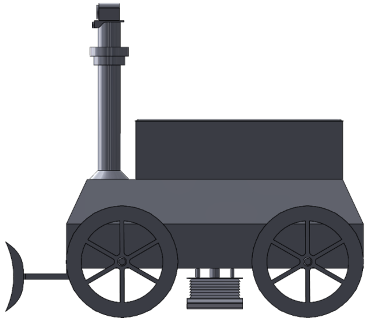
- **Surveyor (S):** High-mobility platform with ground penetrating radar and regolith characterization
- **Excavator (E):** Base platform with articulated bucket ladder for excavation with rippers along chain
- **Hauler (H):** Base platform with coverable bin
- **Compactor (C):** Base platform with a 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

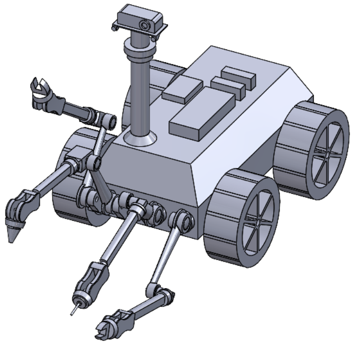
Type	Approx. Duty Cycle	Notional Unit Launch Mass (kg)	Notional Unit Average Power (kW)
Surveyor	90%	500	0.5
Excavator	70%	1,300	2.3
Hauler	70%	1,400	1.0
Compactor	90%	1,500	0.5
Assembler	70%	1,100	2.1
Manager	100%	1,000	0.1

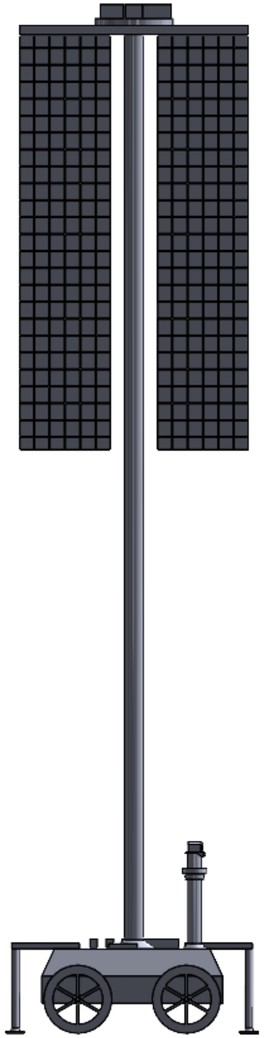

Surveyor


Excavator


Hauler

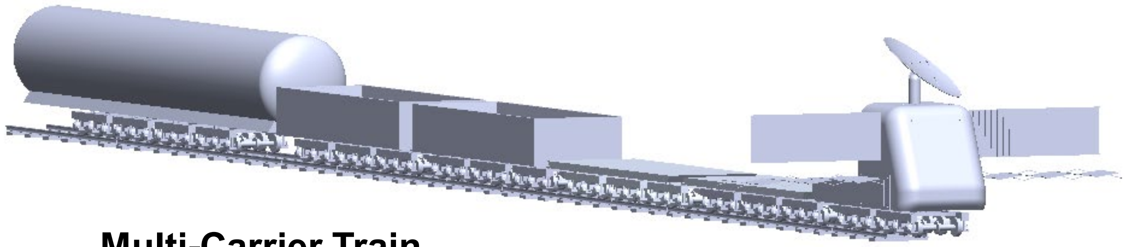

Compactor


Assembler

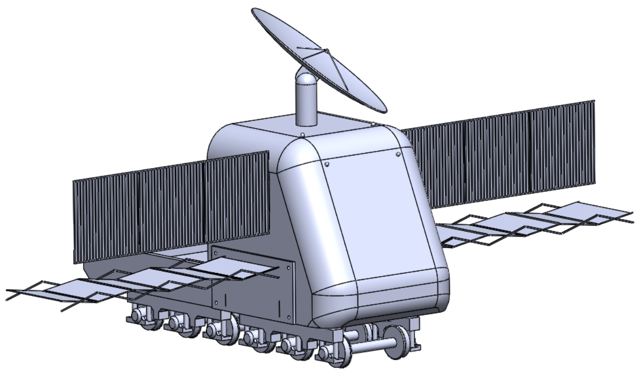

Manager

Source (All): Northrop Grumman Lunar Rail Network Study

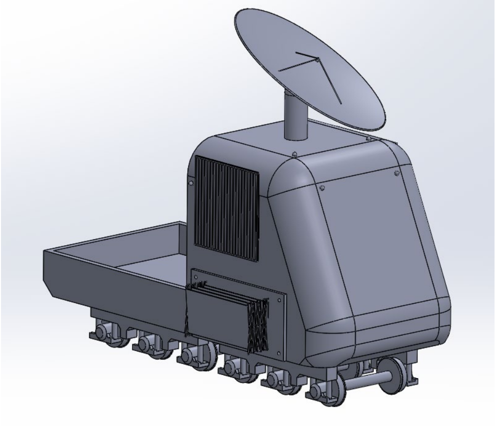
Rail Network Design & Analysis



Multi-Carrier Train



Lunar Day Configuration

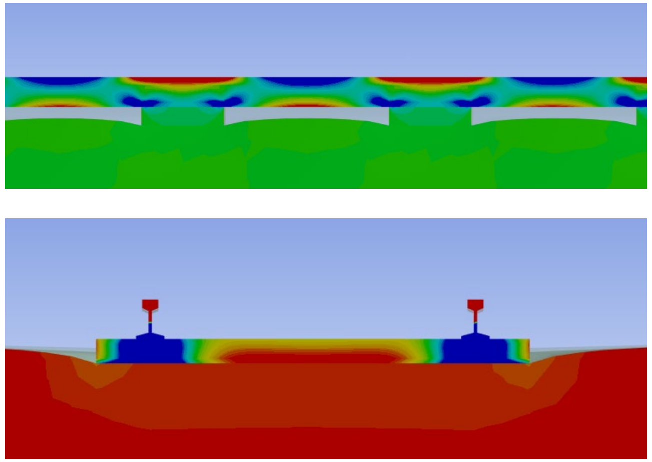


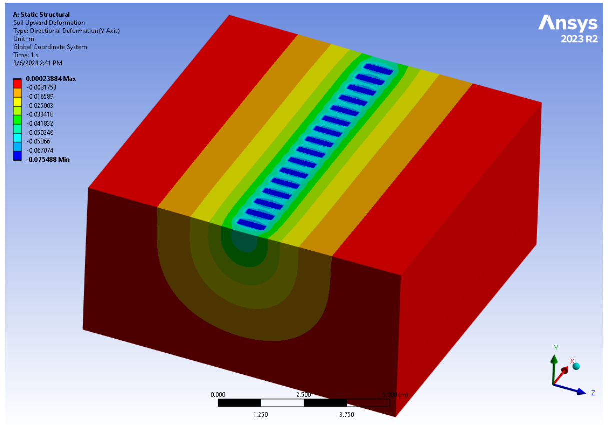
Lunar Night Configuration

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



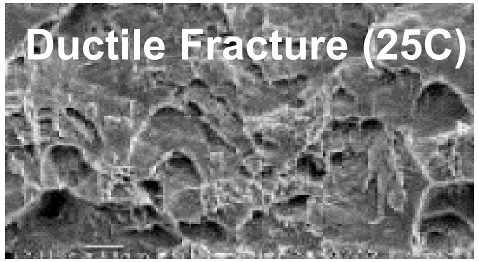


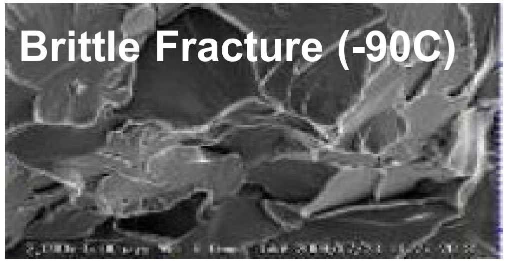
Lunar Soil Deformation

Source (All): Northrop Grumman Lunar Rail Network Study

Lunar Rail Materials Challenges

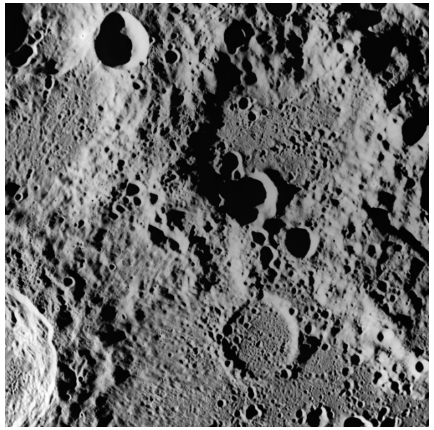
- **Limited In-Situ resource availability**
  - Metal extraction from regolith is challenging
  - Producible alloys differ from common Terrestrial options
- **Extreme temperatures (<-200C to >120C)**
  - Raises concerns for ductile to brittle transitions, thermal expansion, and over-aging
- **Vacuum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



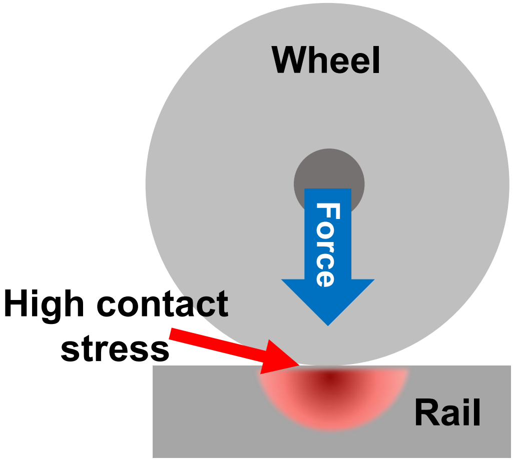


Source: Ductile-to-Brittle Transition and Brittle Fracture Stress of Ultrafine-Grained Low-Carbon Steel - PMC (nih.gov)

Lunar surface

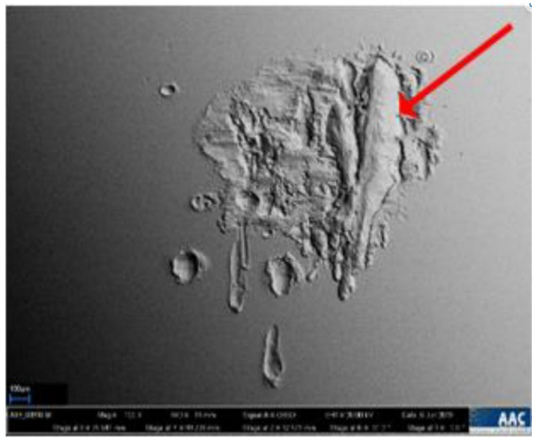


Source: Apollo Image Archive (asu.edu)



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

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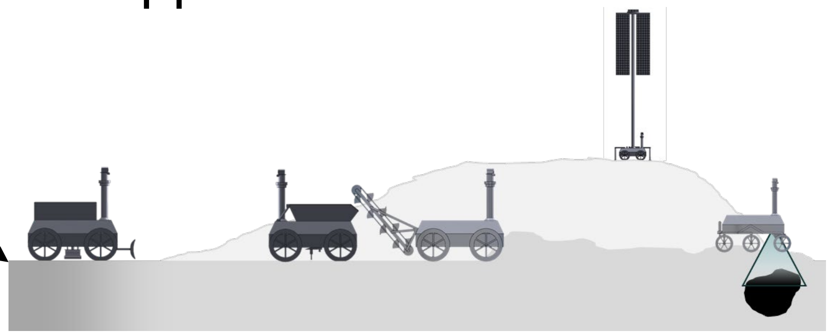
Minimum Viable Experiment (MVE) Phase 1 Objectives

- 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

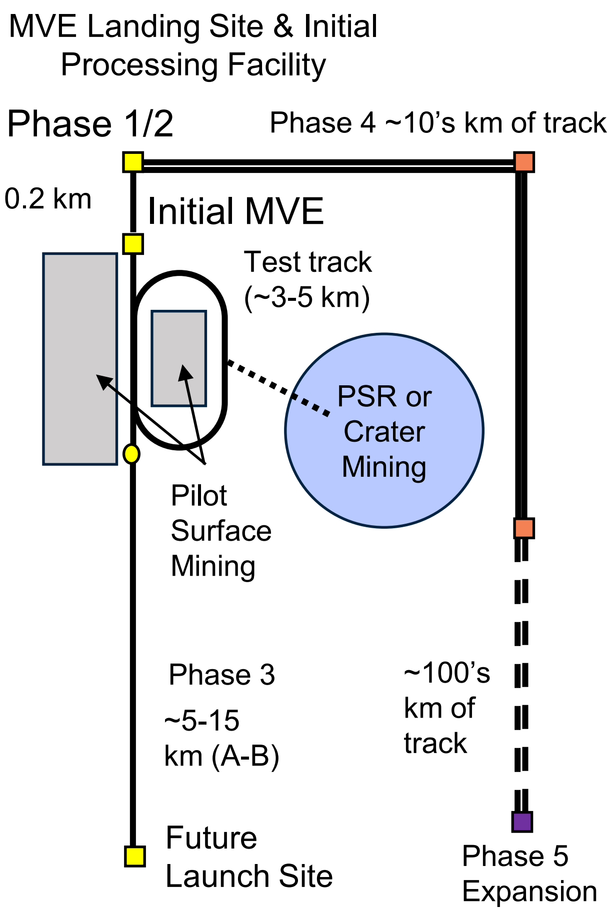
MVE to Pilot to Operational Expansion

- **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



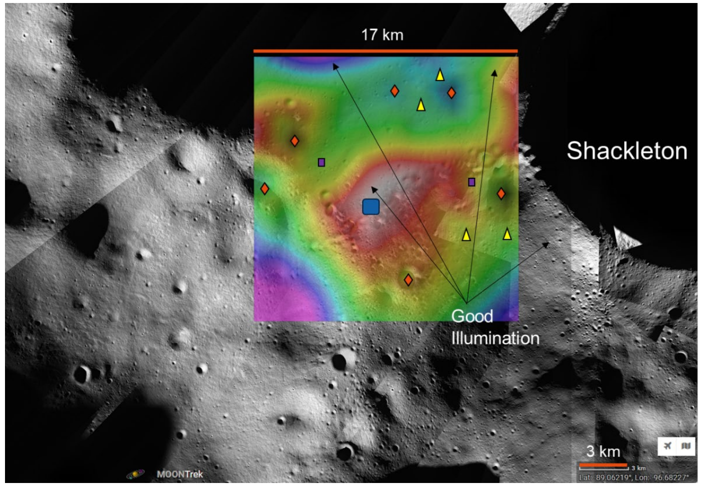
Lunar Rail Network would Scale as Lunar Surface Utilization Grows

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

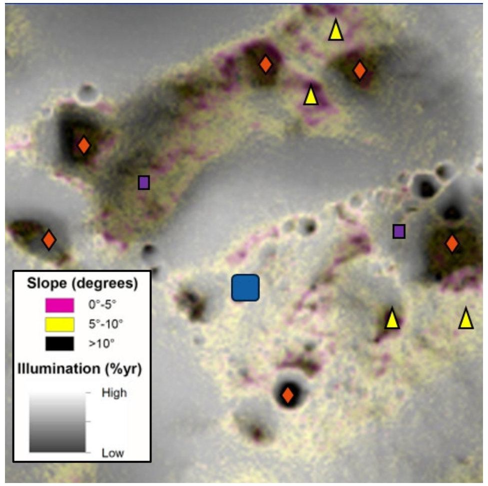
Source (All): Northrop Grumman Lunar Rail Network Study

MVE Site Selection & Expansion

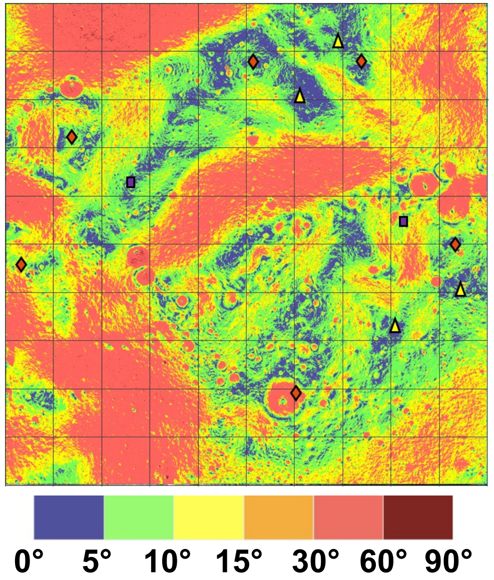
Elevation and Regional Context[1]



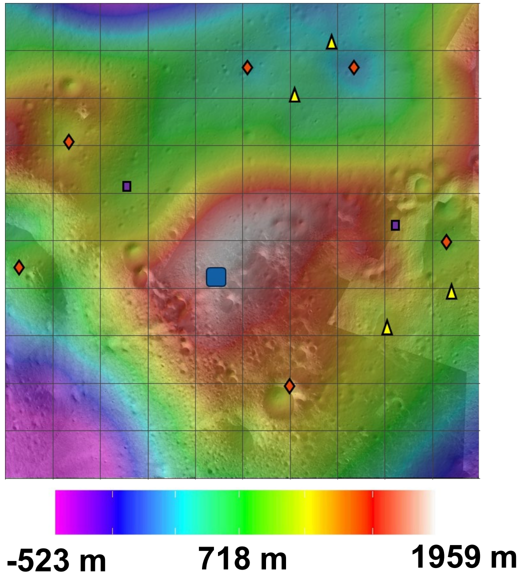
Illumination & Slope[2]



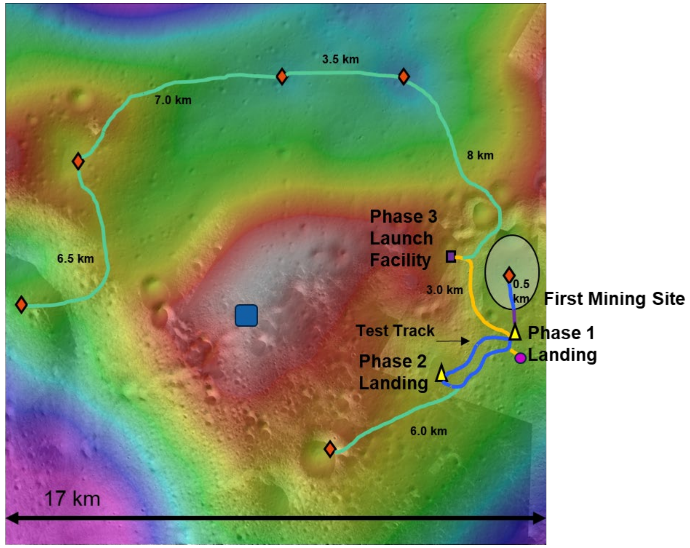
Slope Angle[1]



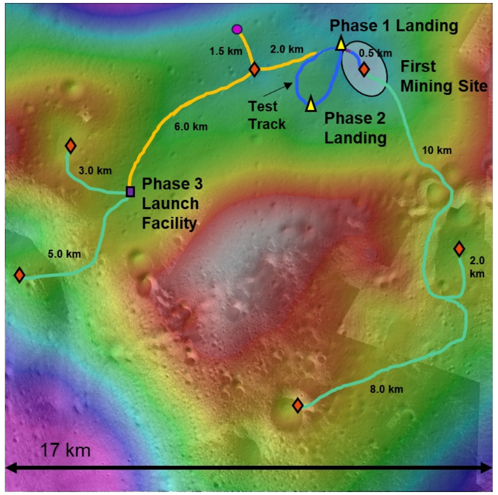
Elevation[1]



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

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

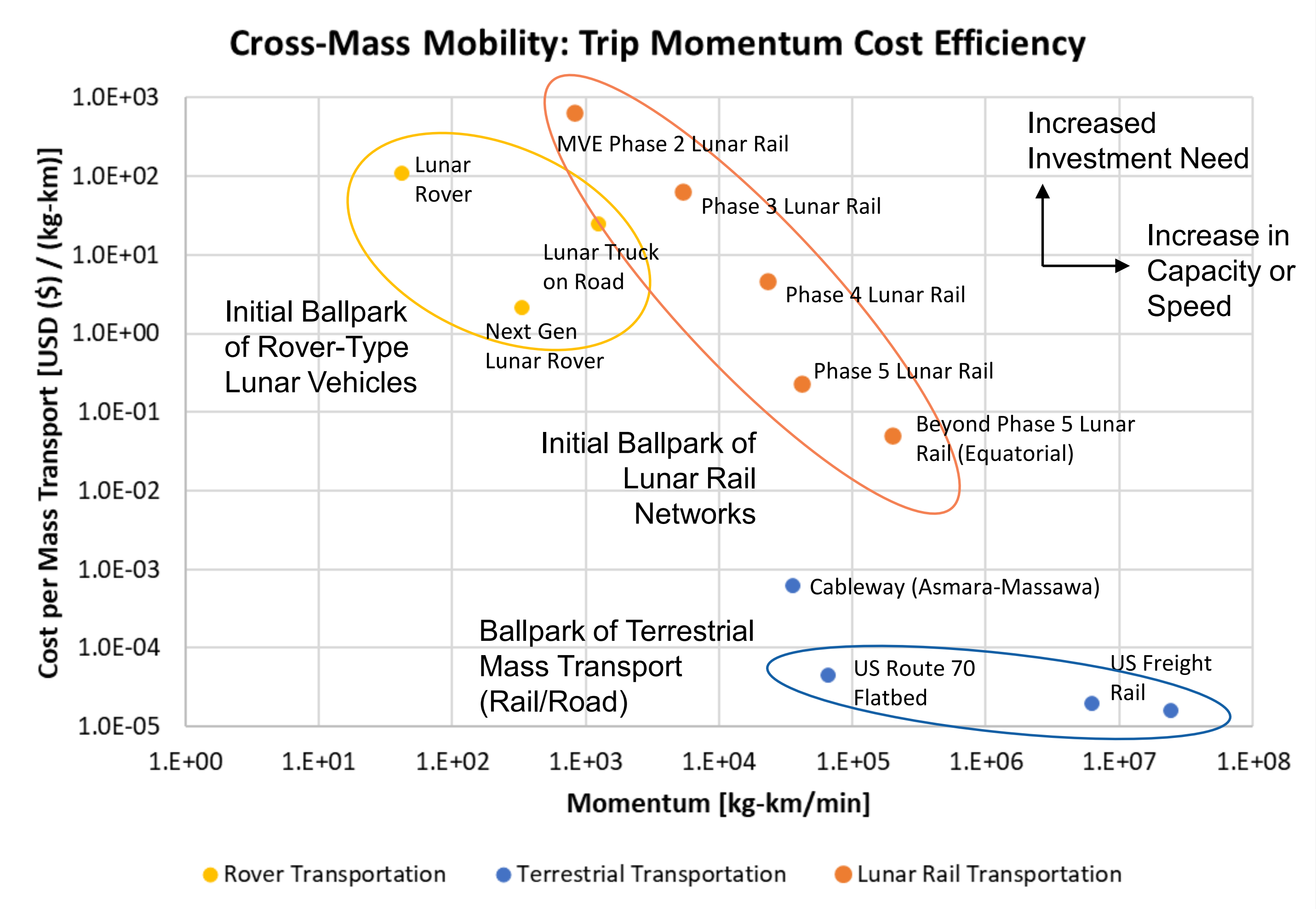
- Max Transport Mass: 100,000 kg – 125,000 kg
- Cost Assumptions:
  - Development Cost - $30,000 per kg[1] (Equipment, Detailed Components)
  - Development Cost - $3,000 per kg (Maintenance Depot Building)
  - Cost of Launch to Moon Base - $10,000 per kg (~7x Falcon 9 to LEO)[2]
  - Cost of Manufacturing 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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