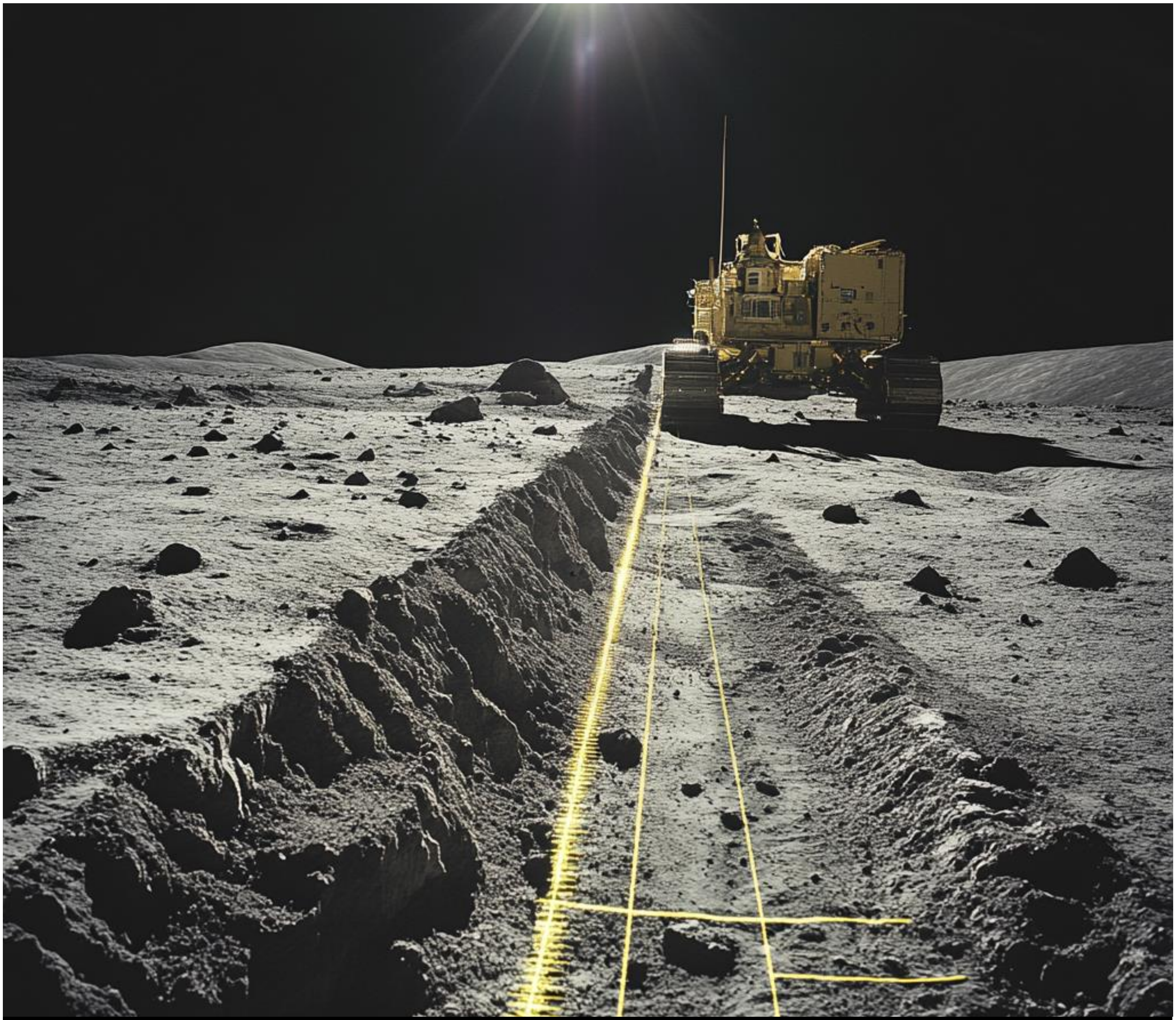

BT-008: Lunar Haul Road Design Concepts

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Series Preamble

This document is part of the *SpaceGeotech Brief Tech Series*, a sequence of technical briefs dedicated to adapting the foundations of terrestrial soil mechanics for lunar regolith conditions. The series builds upon canonical works in geotechnical engineering (Terzaghi, Peck, Lambe & Whitman, Bowles, Das, Holtz & Kovacs) and integrates findings from Apollo "soil mechanics" experiments, NASA technical memoranda, and current Artemis-era mission planning.

The objective is not to propose standards or guidelines, but to provide rigorous adaptations of established soil mechanics equations for lunar conditions. These adaptations aim to create a structured technical reference that academics, engineers, and mission planners can critique, refine, and build upon.

Each Brief Tech presents:

- An adapted formulation of a classical soil mechanics equation for lunar regolith.
- Theoretical justification and newly defined lunar parameters.
- Figures and charts to illustrate applicability.
- Worked engineering examples tied to realistic mission scenarios (e.g., SpaceX Starship HLS, Blue Origin-Blue Moon).

Disclaimer

This document presents the author's independent technical viewpoints under the SpaceGeotech.org platform. The content is **provisional** and intended solely for educational and professional development purposes in the emerging field of extraterrestrial civil engineering.

All frameworks, equations, and values herein are adaptations of terrestrial geotechnical principles to lunar conditions. They are not definitive laws and must not be used as substitutes for in-situ site investigation, mission-specific validation, or detailed engineering design.

Figures and parameters are derived from Apollo mission data, later orbital datasets, and terrestrial analogs. They remain subject to revision as further lunar ground-truth data becomes available through Artemis, Chang'e, and other missions.

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1. Survey of Lunar Mobility Systems and Road Requirements

1.1 Introduction

The ability to move reliably across the lunar surface underpins every future construction, science, and resource utilization activity. On Earth, haul road design in surface mines is informed by decades of experience, surveys of operating fleets, and statistical performance data. For the Moon, no such body of operational data exists. Instead, the foundations for lunar road design must be drawn from a combination of Apollo-era traverses, robotic rover mobility studies, and extrapolations from terrestrial engineering adapted to a radically different environment.

Lunar haulage will not be carried out by 300-ton diesel trucks, but by electric and cryogenic rovers in the 5–20 t capacity range, modular cargo carriers, and eventually pressurized ISRU haulers. Roadway requirements must therefore be framed not in terms of haul truck payload and tire pressure, but in relation to regolith geotechnical properties (L1–L5 zoning), low-gravity traction mechanics, dust mitigation strategies, and the constraints of constructing and maintaining roads without water or atmosphere.

Where terrestrial mines have traditionally built roads with life spans ranging from a single season to more than a decade, lunar roadways must withstand long-duration operations subject to vacuum, extreme thermal cycling (−170 °C to +120 °C), micrometeoroid flux, and abrasive regolith dust. Maintenance cannot rely on routine grading or water-based dust suppression but must instead be achieved through robotic compaction, electrostatic dust fences, and engineered surface treatments such as sintered mats or regolith stabilization.

This section establishes the baseline for lunar road design by reviewing vehicle characteristics, road lengths and alignments, geometric standards, material requirements, deterioration modes, and maintenance strategies, followed by an overview of how design approaches may evolve as lunar operations scale from light rover traverses to heavy cargo transport in support of long-term bases and industrial activity.

1.2 Lunar Haul Vehicles and Construction & Maintenance Equipment

On Earth, haul road design is strongly conditioned by the characteristics of rigid-frame and articulated trucks, with payloads exceeding 300 t and tire diameters of more than 3 m. These machines dictate road widths, curve radii, gradients, and maintenance requirements. On the Moon, however, no such ultra-class fleet exists. Instead, mobility is defined by a new family of vehicles that must be adapted to reduced gravity, abrasive regolith, and the absence of atmosphere.

Haul Vehicles. Early lunar haulage will rely on uncrewed or crew-assisted electric rovers in the 5–20 t capacity class, designed to transport regolith, construction elements, or ISRU feedstock. Their wheel systems will diverge from pneumatic tires: options include rigid metallic wheels, compliant mesh wheels, tracked systems, or hybrid track-wheel assemblies engineered for high tractive performance on fine regolith. Vehicle dimensions will remain constrained by lander payload fairings, requiring modularity in transport and assembly. Unlike terrestrial haul trucks, load distribution per wheel will be significantly lower under 1/6 g, but contact stresses will remain high due to the granular, low-cohesion character of lunar regolith.

Construction and Maintenance Equipment. Earth-based road construction depends on motor graders, compactors, and water trucks for shaping and dust suppression. Lunar equivalents will necessarily be robotic or semi-autonomous units, including:

- Robotic graders with blade or milling attachments for surface levelling.
- Compactors employing vibratory plates or static rollers adapted for vacuum operation.
- Regolith movers (front-end loaders or bucket-wheel systems) for bulk excavation and berm construction.
- Dust management systems, not based on water application, but on electrostatic clearing, surface mat deployment, or regolith sintering units.

The scale of equipment will initially be modest, with payloads in the 1–5 t range, but must be designed for incremental expansion as mission infrastructure matures. Unlike terrestrial practice, where spare parts and fuel are routinely available, lunar construction equipment must be engineered for reliability, modular component replacement, and robotic servicing to minimize the logistical burden of resupply.

In terrestrial haul road design, the vehicle fleet defines the governing parameters for roadway geometry, layer thickness, and maintenance requirements. The same principle applies on the Moon, but with a different operational envelope. Instead of ultra-class diesel trucks, lunar transport will be executed by electric and cryogenic rovers, modular cargo carriers, and pressurized crew vehicles. Payload capacity, wheel type, and vehicle width are therefore the controlling factors for road alignment, cross-section, and berm design.

To establish a baseline for design, representative vehicle concepts ranging from the Apollo Lunar Roving Vehicle to current Artemis-era prototypes and projected industrial haulers are summarized in Table 1-1. This progression illustrates the scaling of lunar haulage systems from light crew mobility to heavy regolith and infrastructure transport, and provides the dimensional framework for determining road standards in subsequent sections.

Table 1-1. Representative Lunar Haul and Support Vehicles

Vehicle Concept	Payload (t)	Gross Mass (t, Earth eq.)	Wheel/Track Type	Length × Width (m)	Notes on Use
Apollo LRV (1971–72)	0.21	0.21	Mesh wheels	3.1 × 1.8	Crew transport, proof of concept
Artemis Uncrewed Cargo Rover	2–3	3–4	Rigid/compliant wheels	4.0 × 2.5	Cargo transport, regolith haulage
Toyota/JAXA Pressurized Rover	2	~10	High-reliability wheels	6.0 × 3.8	Pressurized crew rover, long traverses
ISRU Modular Hauler (Concept)	5–10	8–15	Hybrid wheels/tracks	8.0 × 4.0	Regolith delivery to ISRU plant
Heavy Industrial Hauler (Concept)	15–20	20–30	Tracked	10.0 × 5.0	Future base-scale haulage, large modules

In surface mining, the performance of haul roads depends not only on truck dimensions but also on the range of construction and maintenance equipment available to shape, compact, and preserve the running surface. The same principle applies to lunar operations, where a dedicated support fleet will be required to establish and maintain reliable mobility corridors. While Earth-based mines depend on motor graders, water trucks, and compactors, lunar maintenance must be achieved through robotic and autonomous units adapted to vacuum conditions, abrasive regolith, and the absence of water.

Table 1-2 summarizes representative loading and haul road maintenance equipment reinterpreted for lunar conditions. It highlights the transition from conventional machines to robotic graders, compactors, and dust-control systems, which together form the operational backbone of any sustainable lunar road network.

Table 1-2. Representative Loading and Haul Road Maintenance Equipment

Equipment Type	Lunar Equivalent / Concept	Primary Function on Road System
Hydraulic Shovel / Loader	Regolith front-end loader (robotic or teleoperated)	Excavation of regolith for berms, road base, and stockpiles

Haul Truck	Modular cargo rover or ISRU hauler	Transport of regolith, structural modules, and supplies
Dozer	Robotic dozer with blade attachments	Initial road alignment, berm shaping, rough grading
Motor Grader	Robotic grader or milling unit	Surface levelling, reshaping traffic lanes
Compactor / Roller	Static/vibratory regolith compactor (vacuum-rated)	Layer densification, dust crust formation
Water Truck	*Not applicable*	Replaced by electrostatic dust fences, mats, or sintering units
Maintenance Truck	Autonomous service rover	Component replacement, towing, field repairs
Support Vehicles	Small multipurpose robotic platforms	Transport of tools, mats, sensors, and spares

1.3 Road Length

In terrestrial mines, haul road length is measured in kilometers and evaluated in terms of truck cycle times, pit expansion, and seasonal performance. Lifespan expectations differ in-pit roads may last little more than a year, while ex-pit arterial roads can remain in service for close to a decade. These metrics are tied to continual grading, resurfacing, and the ability to replace surface layers with new aggregates.

On the Moon, the notion of road length must be redefined around mission duration, operational range, and the cost of maintaining a corridor under extreme environmental conditions. Short-term access roads within a landing zone may remain in use for only a single mission campaign of six to twelve months. In contrast, arterial roads linking a landing pad to an ISRU facility or storage depot may be expected to serve for five to ten years, supporting repeated resupply and industrial operations.

The governing limitation is not seasonal degradation, as on Earth, but cumulative effects of regolith abrasion, thermal cycling, and micrometeoroid impacts. Every additional kilometer of prepared road represents a corresponding increase in construction energy, robotic deployment time, and maintenance burden. For this reason, lunar road networks are expected to remain compact, with lengths optimized to reduce energy expenditure while ensuring operational safety. Corridors will be strategically aligned to minimize grades, avoid topographic obstacles, and link only the most essential facilities.

In early phases, road length will be constrained by the mobility range of autonomous haulers (5–20 km), with subsequent extensions possible once maintenance fleets and regolith stabilization methods are proven. Over time, the scaling of roads will mirror the scaling of vehicles: from short rover tracks to permanent transport arteries capable of supporting industrial haulage.

The length of haul roads is a decisive factor in both construction effort and long-term maintenance requirements. On Earth, in-pit roads are often short-lived while arterial roads may last close to a decade. For lunar operations, comparable categories can be established, but service life is determined by thermal stress, regolith abrasion, and micrometeoroid impacts rather than seasonal weathering. Table 1-3 summarizes representative lunar road types, their typical lengths, and expected service lives, reflecting operational scenarios from initial landing access to long-term industrial haulage.

Table 1-3. Representative Length and Service Life of Lunar Roads

Road Type	Typical Length (km)	Service Life (Years)	Notes on Use
Landing Zone Access Roads	0.1 – 1.0	0.5 – 1	Short corridors linking lander pads to staging areas; subject to heavy dust deposition from landings
In-Zone Operational Roads	1 – 5	1 – 3	Connect temporary stockpiles, habitat modules, and early ISRU pilot units
Arterial Roads (Base Infrastructure)	5 – 15	5 – 10	Permanent corridors linking landing pads, ISRU plants, storage depots, and power facilities
Industrial Haulage Roads (Future)	10 – 25+	10+	Long-distance transport between mining areas and processing hubs; feasible only once robotic maintenance is established

1.4 Road Geometry

On Earth, haul road geometry is determined by the turning radius, tire diameter, and braking performance of ultra-class trucks. Cross slopes, gradients, and berms are specified to control water drainage and vehicle stability. On the Moon, where there is no rainfall and no atmosphere, geometry must be reconsidered from first principles while maintaining the central goal of safe and efficient vehicle operation.

Gradients. In terrestrial mines, maximum sustained grades are usually limited to ~10%. On the Moon, lower gravity reduces the weight component acting downslope, but also reduces normal forces and hence traction. Safe sustained grades will remain conservative, generally

<8%, to account for reduced friction and to minimize energy expenditure for electric and cryogenic haulers.

Cross Slopes. Conventional roads are designed with 2% cross slopes for drainage. As there is no water on the Moon, cross slopes are not required for runoff but may still be applied at ~1–2% to help shed loose regolith fines to the roadside and maintain a stable running surface.

Super Elevation. Terrestrial standards use ~4% superelevation in curves. On the Moon, the reduced centripetal force requirements under 1/6 g allow slightly flatter curves, but the overriding constraint is traction on fine regolith. Superelevation should not exceed 3%, and curve radii must be generous to avoid slip or side-drift of rigid or tracked rovers.

Berms. On Earth, berm height is based on 2/3 the diameter of the largest truck tire. On the Moon, berms serve not only as containment for vehicles but also as dust barriers and, potentially, radiation or micrometeoroid shields. Their height should be at least 1.5 m for light rover operations, increasing to >3 m for heavy haulers. Berm geometry will be triangular in profile, constructed from compacted or sintered regolith.

Visibility and Alignment. Dust lofting during lander operations and surface vehicle movement will reduce visibility. Therefore, alignment must ensure long sight distances, minimized sharp curvature, and predictable geometry for autonomous navigation.

Table 1-4 shows the this adapted geometry reflects the balance between vehicle mechanics under reduced gravity and the unique environmental hazards of the lunar surface. The design emphasis shifts from drainage and seasonal performance to traction, dust control, and autonomous navigation safety.

Table 1-4. Representative Road Geometry Parameters

Parameter	Terrestrial Standard	Lunar Adaptation
Sustained Gradient	≤10%	≤8%
Cross Slope	2%	1–2% (for fines shedding)
Superelevation	4%	≤3%
Berm Height	2/3 tire diameter	1.5–3+ m (dust/radiation barrier)
Curve Radii	Based on truck size	Larger radii required; reduced traction on regolith

Note: The adaptations presented are preliminary guidelines that translate terrestrial haul road practice to the lunar environment. Gradients are limited to ≤8% to mitigate traction loss and excessive energy draw in reduced gravity. Cross slopes of 1–2% are retained to enable fines shedding, but must be carefully balanced against stability on low-cohesion regolith. Superelevation is restricted to ≤3% because lateral forces cannot be countered effectively under reduced gravity and weak shear resistance. Berms are significantly higher (1.5–3+ m) than terrestrial standards, serving dual purposes as dust containment and radiation shielding. Curve radii