

10 – Lunar Roads

SUMMARY

This chapter describes how long-distance roads could be established early on by simply robotically smoothing and compacting the lunar dirt. Self-driving cargo and crew vehicles would need periodic way stations / motels where cargo and crew modules could slide from a depleted electric chassis to a fully charged one. Crew vehicles would need to carry their own water shielding to protect against radiation.

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THE VALUE OF LUNAR ROADS

Mobility Within a Region

Roads will obviously become an immediate need just as soon as the first lunar infrastructure. The first roads will be constructed from the regional spaceport to infrastructure and habitats (likely at a Peak of Eternal Light -- PEL). Ideally, the landing pad and infrastructure and habitats will be located kilometers away so that these things will not be sandblasted by any off-nominal landing / crash near the spaceport.

Also, there will be worksites in permanently shadowed regions (PSRs) and surface vehicles will need to traverse between these sites and processing facilities (likely near a PEL). As multiple, separate bases are established, roads will likely connect them. So, for a variety of reasons, a network of roads will be established probably starting in the south polar region.

Access to Global Resources

Looking a bit further out in time, nations will likely wish to establish bases away from the poles towards the equator. It would be desirable for these bases to have overland connection to the polar base(s) in order to benefit from access to the resources located there and high-energy products produced at the PELs. One may think that roads from the poles to the equator will be excessively long -- 2,730 km (1,700 miles). Yes, that

is a fair distance but, as will be shown shortly, it is within the realm of feasibility. Once such roads are built, it would take only three days of continuous driving at 40 kph (25 mph) for products and people to get from the poles to the equator.

Think about it for a moment. When pole-to-equator roads are built, bases near the equator will have access to propellant, water for various purposes, food, and metals. In other words, they will not be lacking just because they are not near the volatiles found in the PSRs. This greatly enhances their viability because the cost of overland transport using electrical vehicles will be a relatively small portion of the production costs.

Much Lower Energy Requirements

It is understandable for one to think that it would just be better to do suborbital flights from a pole to the equator rather than driving all that way. No. The difference in the amount of energy is huge when comparing the need to produce the propellant to accelerate on the suborbital trajectory and then slow down for a safe landing at the equator versus the battery charges necessary to drive the same distance. The rocket equation is tyrannical because one needs to accelerate not just the dry mass of the rocket but the propellant as well. Consider that the kinetic energy is $1/2 mv^2$ so the much faster flight will increase the energy needed as a proportion of the square of velocity. And then you must burn a substantially large amount of propellant to reverse that velocity to zero. Also, water consumed for suborbital hops would mostly not be replenished. There's a great amount of water on the Moon but still, we may want to conserve it especially that water near the PELs at the poles.

The Tesla Model 3 Extended Range can drive 584 km on Earth using a full charge. However, it must deal with a significant amount of air resistance and road resistance due to Earth's full gravity. On the Moon, range will be extended due to lack of air resistance and reduced weight. But compacted dirt roads are softer than hard surfaces so, all combined, electric vehicles on the Moon should be able to get about 900 km range. Compared to the 2,730 km distance from pole to equator, one might think that the vehicle would need about three segments with two waystation stops to recharge. But since the 2,730 km distance is a straight line, deviating somewhat around large craters would increase the total distance by perhaps 10%. So, the lunar EVs may need three waystations between a lunar pole and the equator. Battery pack sizes are a design choice and so their size may be influenced by the distance between equally spaced waystations.

Environmental Benefits

Given that the Moon has thick layers of powdered rock and no life, one might be tempted to think that the Moon has no environment. True, it has no biology to harm nor rivers or air to pollute. But it does have a visual environment that can be significantly defaced. Specifically, because the Moon has no air nor rain, any tire tracks made there will last a very long time. In fact, scientists estimate that tire tracks could last up to 10s or even 100s of millions of years. By having roads and sticking to them, tire tracks can be minimized.

Exploration and Tourism

A network of roads could also assist with both exploration and tourism. By creating very smooth / non-bouncy roads, travel time could be minimized. If one needed to drive off the road system to explore new locations, one could conceive of a different type of electric undercarriage that the crew module could slip on to. This is what I call the StickWalker approach where wheels are replaced with walking legs that are poles with poke vertically into the ground. At an angle, these small holes would be practically invisible.

LEVELS OF ROADS

One can imagine a logical progression from very basic roads to advanced roads with the latter taking much more energy and time to construct.

- **Level 1** - Compacted Dirt Roads - This is where it will start and what will be described in the rest of the chapter. These include telerobotic tractors smoothing paths and compacting the lunar dust so that it is less likely to be kicked up when a vehicle drives over them.
- **Level 2** - Gravel Roads - Also very simple to produce and in fact a potential competitor for compacted dirt roads as the initial form of roads. This would involve a tractor implement what would rake out and sort rocks of various sizes. Gravel size rocks would be placed on the dirt creating a cover over the very fine dust.
- **Level 3** - Sintered Roads - Sintering means using microwaves or concentrated sunlight to melt and fuse together the lunar dirt. The lunar dirt is covered with what is called nanophase iron

which makes it easier to heat. The result is like road pavers but they need to be thick enough to bear the weight of the heaviest passing vehicle. Given how much energy sintering requires, it would take a very long time before significant portions of even a regional network of roads could be constructed using this means.

- **Level 4** - Paved Roads - The Moon has no fossil fuels and water is precious, so asphalt and regular cement is a non-started. Shipping binders from Earth would be cost prohibitive. Ideas like using astronaut urine and blood to create concrete is so stupid it's hard to know why such research is done in the first place (way too little quantities of these materials). But sulphur is present on the Moon and could be used as a binder. But such material would need to be mined and transported. So, this is not a near-term solution.
- **Level 5** - Railroad Tracks - Recently the idea has been promoted to create railroad tracks on the Moon. The clear advantage to doing so is that one can avoid the lunar dust altogether. However, one pair of steel tracks from the lunar pole to equator would require an estimated 6-20 TWh - That's terawatt-hours of energy! That's an incredible amount of energy required just to avoid dealing with dust.

All things considered, compacted dirt roads seem like an easy, early solution to the need for road networks on the Moon.

THE PROCESS OF MAPPING ROADS

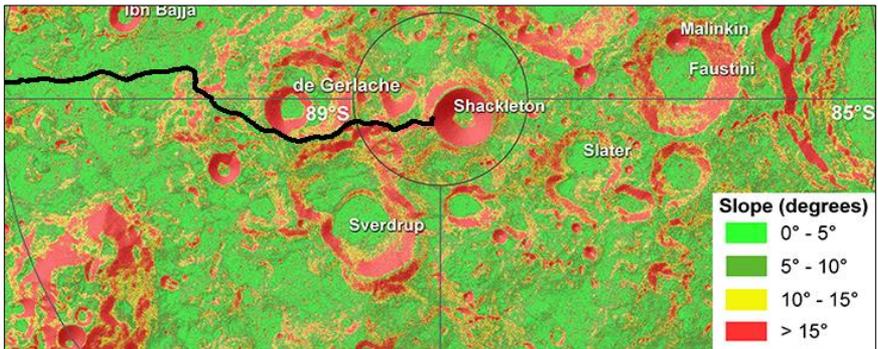
Regional Maps

Locations can and should be identified now about where landing pads, infrastructure, and habitats should best be placed. Given the high-resolution elevation data from the Lunar Reconnaissance Orbiter (LRO), we have, for years now, been able to tell where the PELs are located and where to find relatively flat areas for habitats. A network of roads avoiding steep areas between these locations can be identified. When one looks closely at the LRO images, it becomes apparent that nearly everywhere, lunar dirt has been kicked up and spread all around giving even ridges soft, rounded features. By filling in small craters and driving around the bigger craters, we should be able to create roads avoiding steep areas between any of places where we will have assets.

However, the many PSRs of the lunar south pole have not yet been prospect with on-the-ground data. So, which PSRs contain sufficiently high levels of volatiles making it worthwhile to harvest those locations? We don't know. So, there will need to be a robotic prospecting phase, and the results of those studies will identify which areas will become volatile harvesting "mines". So, the regional roadmap will be incomplete until after we get that data.

Global Maps

Slope angle is probably the most significant factor determining where a lunar road can go. It is not reasonable to have vehicles driving up or down steep slopes no to have to cut into a side hill to make a road more level (high side to low side). So, we would start with the LRO data that has a resolution of 25 to 50 cm. From the elevation data, the Space Imaging Center at the University of Arizona (Tucson) has produced slope maps. These maps would be particularly useful in identifying what path deviations would be needed to avoid areas of excessive slopes. Very high resolution from one of the RoadBots could be used to refine the original global maps.



SMOOTH DRIVING

Very Smooth Roads

The keys to making compacted dirt roads work would be to ensure that they are very smooth and compacted as much as possible. Smoothing largely involves removing rocks (which can be done with a rock rake implement), filling in small craters (which are ubiquitous), compacting, grading, and compacting again. The hope is to make roads so smooth and compacted that vehicles can quickly drive along the road without significantly bouncing.

Self-driving Vehicles

Practically all vehicles on the Moon will be self-driving. It will be very easy to implement this because lane keeping is now fairly common and, on the Moon, there is no traffic, stop lights, dogs running onto the street or any such thing. So, just driving along a road will be quite simple.

Autonomous Transport of Resources

The Innovative Plan for Space Development foresees telerobots preparing and compacting a network of Level 1 dirt roads on the Moon. Automated vehicles could drive on those roads and record the ups and downs and any loss of traction while going around corners. This recording could be used by later vehicles to safely traverse the road at a maximum but safe speed.

These vehicles could take international astronauts and tourists to regional destinations without having to consume a tremendous amount of energy electrolyzing water into propellant for a suborbital hop. Traveling at about 25 mph from a polar base to the equator would take about 3 days. There would need to be solar-powered charging way stations. Perhaps cargo and crew modules could be transferred between electric undercarriages to eliminate waiting times.

But also, these vehicles could be used to transport water and other volatiles from the poles to bases or settlements in other parts of the Moon. Likewise, autonomous vehicles could transport mined materials such as potassium and phosphorus fertilizer from mines to other bases including to the poles. In this way, no part of the Moon would be without the resources they need for settlement.

Driving Speeds Using Accelerometer Recordings

So, one can fill in small craters but there will be areas that have bumps that are too large to be bulldozed down. So, there will be unavoidable ups and downs and, if the vehicle is driving too quickly, in 1/6th gravity, it will be easy for the vehicle to "catch air" and potentially lose control resulting in tumbling over. That, of course, would be very bad. So, how can this be prevented? Specifically, there are several ways that vehicles on the Moon can know where along the course they are. Previous vehicles traveling along the road can record and transmit results from the accelerometer and later vehicles can slow down in those areas where they are about to lift off the ground if they go too fast. In this way, good traction can always be assured while traveling at a relatively fast but safe speed.

Tilting Platform

Since long-distance travel can last for up to three days, passengers could sleep while the self-driving vehicle is moving. If the vehicle is driving up or down or tilting a bit to the left or right, then sleeping passengers could end up rolling around inside their vehicle. To avoid this, an active leveling system could ensure that the platform that the crew module is attached to always remains level within the angle limit that the roads are designed to meet.

THE PROCESS OF CONSTRUCTING ROADS

The RoadBots

To construct the roads, there would be a team of tractor-like robotic vehicles. Ideally, they would conduct their work autonomously but if that technology hadn't been developed yet, the work could also easily be done telerobotically. RoadBots would consist of robotic tractors with:

- A tall mast with lidar to scan many meters ahead allowing the identified road path to be adjusted to bypass craters too large to be filled in.
- A front blade to push regolith into small craters and to create a generally smooth path.
- A rock rake to remove rocks leaving behind compactable material.
- An electric steamroller to compact and smooth the road.
- Repeat use of the front blade and compactor would ensure that the path is as perfectly smooth and compacted as possible.

Grading the Roads

As previously mentioned, the terrain through which the road will be placed may be at an incline forward and back or left and right. Going forward and back we largely have to drive at that angle. We can do a bit of cutting and filling to level out the path but not very much. But we can cut into a right-left incline a bit, perhaps as much as 15 degrees which would come to about one tonne of material removed for each meter going forward.



Teams of RoadBots autonomously constructing compacted dirt roads.

Simultaneous Teams

An important point is that the speed of how fast a lengthy compacted dirt road can be constructed is how many teams of RoadBots are constructing the road simultaneously. So, if there are five RoadBot teams working on a 1,900-mile pole-to-equator road simultaneously and each team is moving forward at 1 mph then it would take 80 days to finish the road. That comes to 5.7 lunar daylights (14 Earth days) to complete the road which is a reasonable amount of time for such an important project. Of course, one could fiddle with the variables such as increasing the number of RoadBot teams and/or choosing a different project time.

Maintaining the Roads

The problem with dirt roads is that, as vehicles drive over them, they can develop longitudinal ruts or wash boarding. Self-driving vehicles could be directed to drive on one side or the other of previous ruts to prevent ruts from deepening. But eventually the roads will need to be fixed. But the solution is simple. As needed, have two RoadBots drive along the route. One would use a blade and the other would compact the road again. In this way, the roads could be adequately maintained indefinitely.

PONY EXPRESS WAYSTATIONS

Swapping Cargo and Crew Modules

As mentioned before, way stations are where electric chassis can be charged while crew or cargo vehicles are incoming. At the waystation, depleted vehicles can drive up next to a fully charged electric chassis. Then, the crew or cargo module can slide between the two chassis so that those modules can immediately continue their journey. This is analogous to the Pony Express mail system in America's old West where mail-carrying riders could swap fresh horses and continue their rapid journey. Alternately, passengers could dock with the waystation and spend a while resting and stretching their legs or even spending the night.

Waystation Design

Given the charging needs, the way station will certainly need a large field of solar panels that could charge a bank of batteries during the lunar day (15 Earth days). The scheduling of trips will need to consider the vehicular traffic and battery sizes to take into account the demand for charging and different parts of the lunar day.

Also, given the accommodation needs of passengers, the waystation should be designed to have lounge and kitchen areas, bedrooms, bathrooms, and the ability to provide life support and handle human and other wastes.

The diagram below shows how a sintered turnout would have a parking spot where robots could dust off the vehicle before it advances to dock with the way station. Passengers could then move from the pressurized vehicle into the way station. Waste would be stored in an exterior container which would be periodically removed and transported to where that valuable waste could be processed back into useful materials. As the traffic increases, additional solar panels, batteries, and motel space could be added.



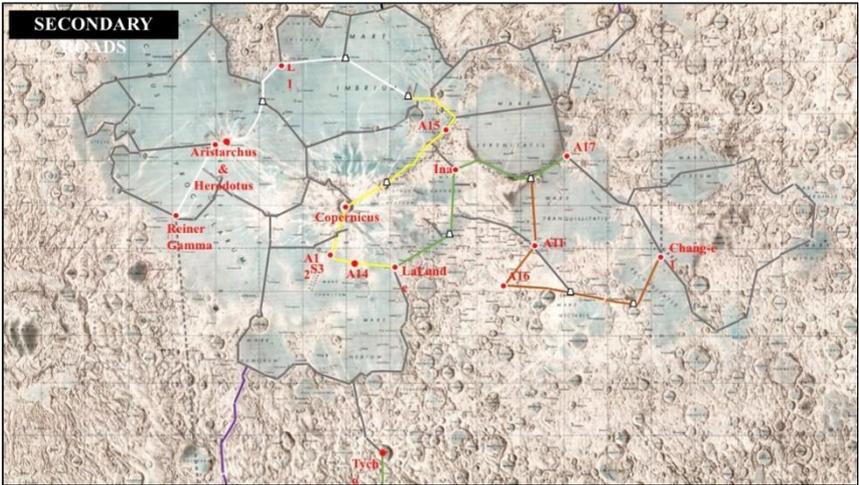
A conceptual diagram of a waystation.

A ROAD NETWORK

So, what would drive the design of the global road network? In the long run, it will probably be what places on the Moon will be repetitively visited by explorers and tourists. Certainly, sites with historic artifacts such as the Apollo landing sites would be on the list. Also, certain sites with dramatic landscapes like the edge of large craters hundreds of kilometers wide would be of great interest. Certainly, the opportunity to safely explore lava tubes would be fun. And remarkable hotels, a day's ride between sites of interest would be something to look forward to.

The Lunar Grand Tour

In the image below, the Space Development Network has imagined a network of roads connecting major sites of interest. Then, secondary roads often following the edge of mare basis would allow travelers to drive along relatively smooth roads while having dramatic basin walls to one side. Overall, this Lunar Grand Tour would connect points of interest while allowing options for taking paths that would see some impressive sites.



Hypothetical map linking likely tourist sites with secondary roads. Credit NASA