

# **Best Practices for the Testing of Planetary Roving Vehicle Mobility Systems and Tires**

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## **Abstract**

NASA has an extensive history of conducting mobility testing on planetary tires, rovers, and mobility subsystems. This paper contains a summary of the best practices and lessons learned from past test approaches, as well as from relevant test methodologies external to NASA, with a focus on tires and mobility systems. It is intended to be a resource for future planetary rover developments. This document, which will be released in two phases, serves two objectives: 1) compile the existing knowledge of mobility related testing within NASA; and 2) identify major gaps in mobility related test needs and suggest potential paths forward. This first release of the document (early 2025) captures information based on the authors' existing knowledge and an abbreviated literature review. A more thorough version will be released in late 2025 and will include more information on test methods external to NASA, as well as additional lessons learned through further investigations. The Lunar Terrain Vehicle (LTV) is used as case study to help identify major test needs; however, this document is intended to be applicable to a wide range of potential missions. Though no current mobility standards exist for the testing of planetary tires and mobility subsystems, future motive is to utilize the information from this whitepaper to guide the development of NASA mobility test standards.

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# 1 INTRODUCTION

## 1.1 Motivation

NASA’s “Moon to Mars” architecture [1] identifies plans for long-term exploration of the lunar and Martian surfaces and calls for an increase in participation of partners external to NASA, including industry, academia, and the international community. This new generation of planetary exploration brings new technical challenges, a greater cadence of surface vehicle missions, and a broad array of vehicle providers. To successfully carry out these extended missions, testing on rover tires and mobility systems will be critical, both for technology development purposes as well as to verify the ability to meet key requirements. NASA has a history of conducting testing of mobility systems dating back to the Apollo program; however, much of the best practices and lessons learned has not yet been shared with the public. In addition, there are new test needs that may not have any heritage within NASA and may require new test methods and capabilities. This paper serves to address these needs through the following goals:

**Goal #1: Compile the existing knowledge of mobility related testing within NASA**

**Goal #2: Identify major gaps in mobility related test needs and suggest potential paths forward**

## 1.2 Scope

This paper will be released in two iterations. This current document is the first iteration and strives to quickly disseminate relevant information to the external partners. It primarily consists of existing knowledge held by the authors of the paper, who have extensive experience in this area, along with information collected through an abbreviated literature review. It can be considered a high-level summary of the state of the art of mobility testing for planetary rovers and identifies existing resources (such as technical papers and industry standards) that can be utilized at this time. It also identifies gaps in testing capabilities and addresses associated potential risk areas.

The second iteration of this document is anticipated to be released in late 2025. That revised version will encompass additional knowledge gained through a more extensive literature review, discussions with experts in related fields (such as terrestrial vehicle testing), and from internal assessments of test methodologies.

The scope of this paper will be limited to the evaluation, via testing, of planetary roving vehicle’s mobility sub-systems with respect to traversability. The focus will be on how the rover interacts with the terrain, thus tire testing is a major part of these assessments, though full system level test methods are addressed as well. Other sub-systems of a rover, such as navigation control, sensing, and autonomy, though relevant to traversability, are outside the scope of this document. However, it should be noted that the techniques and methods presented here *can* still be utilized for assessing those other sub-systems as well, and in many cases a full rover system or sub-system may be tested as one unit. Also, there will likely be test methods and best practices discussed here that have commonalities to methods used for terrestrial vehicle testing; however, the intent is to focus on the unique needs of planetary roving applications, thus factors such as environment and gravity must be considered.

**This paper is not intended to be an all-encompassing guide for all mobility-related test practices.** There will likely be test types and details that are not addressed here but may be of importance for a given mission; it is simply not feasible to address everything at this time. The authors are using best judgement to identify what we believe are the major test types of interest to the planetary rover development community. New types of tests or details may be added in the second iteration based on initial feedback from external partners to this first iteration of the document. **These best practices also should not be taken as “standards”.** It is likely that NASA standards may be produced from this information in the future, but that is not the intent of this paper. Interested parties should use this information as they see fit in the development of their own unique mobility test programs.

*Note on the use of “wheel” vs. “tire”*

Conventionally, the wheel represents a rotating component that converts torque to thrust, while the tire represents a component on the wheel that interacts with the terrain. For pneumatic terrestrial tires, there is a clear distinction between the two (the tire is the pneumatic portion). However, for non-pneumatic tires there is not always a definitive distinction. In the field of planetary robotics, both terms are often used to describe the full component, thus they will both be used in this paper interchangeably.

### **1.3 Discussion on mobility-related requirements for LTV**

Though this document aims to serve a range of planetary roving vehicle applications, the Lunar Terrain Vehicle (LTV) is used here as a case study for identifying major testing needs. The LTV [2] is to be a commercially developed and operated roving vehicle that could traverse the South Pole region of the Moon starting in 2029 and support NASA and commercial missions for 10 years, operating in both crewed and uncrewed modes. In addition to being unique in that a commercial company will be developing, delivering, and operating the rover, there are also very challenging mobility related requirements that must be met. For discussion purposes, below are a summary of key mobility-related requirements for LTV that may require testing:

*Longevity and durability.* The LTV is required to drive 1300 km annually for a total of 10 years, which means that tires and mobility components must be operational for long periods of time under challenging environmental conditions (dust, radiation, cold/hot temperatures) without major losses in functionality and performance. For perspective, the longest distance traveled previously on a planetary surface was the Mars Opportunity Rover at 45 km [3].

*Soft soil performance.* The LTV is required to safely traverse up and down 20° slopes on the surface of the Moon and traverse up to speeds of 15 km/hr on level ground. The rover must also be able to hold position on a 20° slope while conducting various operations.

*Obstacle traversal.* The LTV is required to traverse obstacles up to 30 cm in height and negative reliefs up to 30 cm in depth, as well as traverse craters up to 2.5 m in diameter.

*Environmental survival and performance.* The LTV is required to survive no less than 150 hours of continuous darkness at temperatures down to -212° C (61K), and traverse into and

out of permanently shadowed regions (PSRs) for up to 2 hours at temperatures down to -237° C (36 K). In addition to temperature, environmental factors such as dust and radiation must be considered.

*Load carrying capacity.* The LTV is required to transport at least 800 kg of payload at full performance levels, and 1600 kg of payload at reduced performance levels.

*Operating speed.* The LTV is required to operate at a maximum speed of no less than 15 km/hr on flat terrain.

## 1.4 Summary of test types discussed in this paper

As mentioned in Section 1.2, this paper is not all-encompassing of every mobility test needed for LTV or other planetary rover applications. Based on past experiences and an assessment of the LTV requirements, the following test types are presented in this document. Additional test categories may be added in the second iteration.

- Full Mobility System Tests:
  - Drawbar pull / soft soil traction
  - Slope performance (upslope, downslope, and cross-slope)
  - Obstacle traversal (rocks, craters, and other terrain features)
- Single-wheel Tests:
  - Drawbar pull / soft soil traction
  - Endurance related tests (fatigue, wear, impact, etc.)
  - General characterization tests (rolling resistance, stiffness, vibration, etc.)

## 2 SUMMARY OF KEY TAKEAWAYS

Though the following sections (Sections 3, 4, and 5) provide recommendations related to specific test types or methods, the authors felt that there were some points applicable to multiple test types that should be highlighted up front. These points will all be addressed again later in the document.

### 2.1 Summary of major lessons learned

Each section in this paper identifies lessons learned for specific test types or methods. The list below summarizes the major lessons the authors feel should be emphasized.

Table 1: Summary of major *lessons learned* related to mobility testing

| Lesson Learned                                                                                                        | Description                                                                                                                                                                                                                                                                                                                                                               |
|-----------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>It is important to account for combined loading cases on tires, especially with regards to durability testing.</i> | Previous experiences have shown that the failure modes of rover tires are often not due to force in one direction, but rather the combinations of forces in multiple directions. Single-axis tests are still valuable (ex. for stiffness and fatigue assessments), but the durability of tires needs to be assessed under realistic, or conservative, loading conditions. |

|                                                                                                                                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                     |
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| <p><b><i>It is not feasible to evaluate all operating conditions with one test.</i></b></p>                                                                                         | <p>In general, it is not feasible to produce one test or test rig that accounts for all environmental, atmospheric, terrain, and operational conditions in a lab. The unique environment of the lunar South Pole only exacerbates the difficulty.</p> <p>Conditions that should be accounted for include the following: forces on wheels (function of gravity, rover mass, driving modes, etc.), vacuum, temperature, radiation/ultraviolet exposure, slopes, obstacles/reliefs, and lunar regolith/dust. Existing test facilities can typically only account for a subset of these at best, and due to the scale needed for some, it is unrealistic to attempt to build one facility that covers everything.</p> <p>Thus, a set of tests and models will need to be strategically selected to properly reduce risk and assess the ability to verify and validate against requirements. Carrying out subassembly and component level tests early on in the test program to uncover unknown or unexpected issues can be crucial.</p> |
| <p><b><i>Regolith simulant choices must be made with specific test needs in mind.</i></b></p>                                                                                       | <p>Just as with test facilities, there is no one simulant on Earth that matches all the properties of lunar regolith, due to the differences in environmental conditions. In addition, the lunar surface consists of multiple regolith types with a range of properties; the most conservative regolith type for each test is typically not the same. It is important to identify the appropriate simulant for each test type. For example, one simulant may be ideal for assessing soft soil traction (low cohesion, low friction angle) but a different one may produce a greater dust challenge (smaller and more angular particles).</p>                                                                                                                                                                                                                                                                                                                                                                                        |
| <p><b><i>Historical test methodologies can and should be leveraged, though it's important to be aware of differences in priorities and limitations from those programs.</i></b></p> | <p>Much of the test approach taken for the Apollo Lunar Roving Vehicle (LRV) should be considered (see Section 5.2), but it's important to note that the LRV had a strict packaging requirement that does not exist for LTV and other lunar rovers. Similarly, there are many useful lessons learned from the Mars rover programs, but those rovers operated at very slow speeds and thus inertial and dynamic effects were considered minor with respect to surface testing. In addition, longevity and cold temperature operation are much greater challenges for LTV than they were for both of these cases. It is recommended to look to these programs when developing test campaigns but be cognizant of areas where different approaches may be needed.</p>                                                                                                                                                                                                                                                                  |

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|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b><i>There are benefits to performing tests on full vehicle or system, when possible.</i></b></p>                                                                                            | <p>Because the performance of a rover is not based on the tires alone, it is best to conduct full system tests where applicable. However, due to the size and scale needed, this is not always feasible, especially early in the tire development process. For scenarios where full vehicle tests are not feasible, models and/or testing should be used to properly set the test conditions for a single tire. For example, when conducting durability tests on a tire, the proper loading conditions need to first be established via full vehicle tests or simulations.</p>                                                                                                                                                                                            |
| <p><b><i>Because compliant tire vibration response can be difficult to simulate, relevant vibration testing should be conducted early in order to correlate the system-level models.</i></b></p> | <p>As opposed to rigid wheels, compliant tires are more likely to exhibit things like nonlinear behavior or have complex internal interactions. These can make producing a finite element model correlated to the vibration response more challenging. At a minimum, this correlation is typically required if a wheel has modes below the project specified frequency threshold.</p> <p>As the level of challenge will be design dependent, it is prudent to perform the relevant vibration testing as soon as realistically possible to either verify that the tire is above the frequency threshold or gather the information against which to correlate the model. For correlation, it can be beneficial to understand the interface forces/modal effective mass.</p> |

## 2.2 Summary of major gaps and risks

Table 2 is a summary of the major knowledge gaps and risks related to mobility identified in this paper.



Table 2: Summary of major gaps related to mobility testing

| Gap                                                       | Description                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Unknown terrain conditions at the lunar south pole</i> | <p>Very little data exists on the terrain conditions at the lunar south pole; inferred properties are based on Apollo equatorial terrain data as well as known environmental conditions.</p> <p>While there are numerous lunar simulants, a majority of which are designed based on equatorial surface data, there are currently no NASA standard lunar regolith simulants for the south pole. For mobility testing, NASA has released a “Lunar Regolith Simulant User's Guide” [4] to provide information on currently available simulants, best use cases, and safety practices.</p> <p>Further work is needed to better assess the range of possible terrain types at the lunar south pole, and to identify appropriate simulants and preparation techniques to mimic these in a laboratory. In addition, simulant selections need to be specific to a given test case.</p> |
| <i>Effect of gravity on regolith and simulants</i>        | <p>It is well known that gravity has an effect on the interaction between tires and regolith; NASA has historically accounted for this by adjusting the weight-on-wheels and using metrics such as cone index gradient to produce lunar-like terrain reactions for testing.</p> <p>However, recent studies [5] have raised doubts about the reliability of using cone index gradient to assess soil strength under different gravity fields and have suggested a potential greater effect of gravity on soil than previously understood.</p> <p>Further work is needed to better understand this effect of gravity and validate (or update accordingly) laboratory test approaches. In the near term, it is recommended to apply model uncertainty factors to the results to account for a potential variation.</p>                                                            |

|                                                                                       |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|---------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b><i>Inertial/dynamic effects during tire-terrain interaction testing</i></b></p> | <p>For slow-moving roving vehicles (on the order of 5 cm/s or 0.18 km/hr) like VIPER and all the Mars rovers to date), NASA has assumed that for most mobility operations, such as climbing a slope or traversing an obstacle, effects due to inertia and acceleration are negligible. This allows for laboratory testing with reduced mass vehicles to simulate the correct in-situ weight and thus tire contact down-forces.</p> <p>However, for large fast-moving vehicles, such as LTV (designed to operate at speeds up to 15 km/hr), there are likely major effects due to dynamics that will not be correct when using reduced mass (and thus inertia) test vehicles. Though quasi-static laboratory testing (such as drawbar pull/traction) can still provide meaningful data, the dynamic effects of inertia, acceleration, and impact need to be accounted for, especially for cases where a rover is encountering obstacles.</p> <p>Note that these effects also impact single wheel tests in the same manner and for the same reasons. There are no known facilities able to properly simulate these effects at the tire level. Future work is needed to identify solutions.</p> |
| <p><b><i>Challenge to performing standard life testing of tire or rover</i></b></p>   | <p>For tires and other key mobility components, NASA has traditionally taken an approach of testing to two to four times life to ensure confidence in the life of the tires and meet verification requirements.</p> <p>However, for long duration (time and distance) missions, such as LTV, this poses a potential schedule and cost risk. As an example, the total distance required for the LTV rover is 1,300 km/year over 10 years. Using the minimum required max speed of 15 km/hr and assuming no tire replacements would mean it would take at least 3,467 hours, or 144 days non-stop, to do a 4x life test—not accounting for downtime due to rig maintenance, inspections, time for thermal changes, etc.</p> <p>New practical approaches should be investigated to ensure the life of the tires and other mobility subsystems.</p>                                                                                                                                                                                                                                                                                                                                              |
| <p><b><i>Lack of full environmental test capabilities</i></b></p>                     | <p>The lunar south pole introduces environmental conditions that are beyond what has been tested to date. Most notably, the permanently shadowed regions are expected to reach temperatures down to 40K; no known facilities exist that can test tires or rovers down to those temperatures. In addition, the effects of environmental conditions on tires (temperature, radiation, dust, vacuum, etc.) are expected to be coupled; thus, it may not be sufficient to test in each condition separately.</p>                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                 |

|                                                                            |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |
|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b><i>Lack of test standards for planetary rovers and tires</i></b></p> | <p>Most existing tire characterization test standards are intended for terrestrial applications where loads, speeds, terrain, and environmental conditions are all very different than on the moon or Mars. They are also largely for pneumatic tires.</p> <p>As an example, rolling resistance tests, which are inherently difficult to run, are made even more complicated by applying the current standards to off-road planetary vehicles. These standards were typically designed for vehicles of much heavier loads, driving on highway-type pavements, with much faster speeds.</p> <p>While in some cases these existing standards may be sufficient, effort is still needed to identify or produce new standards specific to the needs of planetary rover tires.</p> |
|----------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|

### 3 FULL MOBILITY SYSTEM TESTS

#### 3.1 Drawbar Pull / Traction

##### 3.1.1 Introduction

Drawbar pull (DP) testing is a common method used to assess the tractive potential of off-road vehicles. Historically it was developed to measure the towing capacity of tractors but has been adapted over the years for other ground vehicle applications, including planetary rovers (see Figure 1). The testing can be done on a full vehicle, a subsystem of the vehicle, or directly on the tires. This section will discuss methods for conducting full vehicle or subsystem tests.



Figure 1: (a) Farming tractor towing a drawbar load. (b) Roving vehicle undergoing drawbar pull testing

##### 3.1.2 Applicable resources

In 2016, NASA released a guide on conducting vehicle drawbar pull tests entitled “Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing” [6]. Though it is not an official standard, the

methods presented in this paper have been used by various NASA and commercial rover test programs. It consists of three parts: 1) an overview of the testing concept, including detailed discussions on metrics, 2) a discussion on the terrain preparation methods and characterization used at NASA Glenn Research Center (GRC), and 3) an analysis of the various test parameters. It compiles information gathered via literature reviews along with lessons learned through years of testing at NASA. A high-level overview of that work is presented here. For more details, we recommend reviewing that paper.

NASA also released the “Lunar Regolith Simulant User’s Guide: Revision A” in October of 2024 [4]. It provides specifications of various lunar simulants for the south pole, as well as safe use practices. It should be noted that it is limited to simulants that match the mineralogy of lunar regolith, so some simulants, such as GRC-1, are not represented.

We also recommend the “Updated Standards of the International Society for Terrain-Vehicle Systems (updated 2020)” for general definitions of terminology and metrics related to off-road vehicle testing. These three references are listed in Table 3.

Table 3: Recommended resources related to vehicle drawbar pull testing

| Reference                                                                             | Description                                                                                                                        |
|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| <i>Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing</i> [6]                  | Detailed description of drawbar pull test procedures utilized at NASA GRC, including discussions on theory and terrain preparation |
| <i>Lunar Regolith Simulant User’s Guide: Revision A</i> [4]                           | NASA guide on known mineralogical lunar regolith simulants for the lunar south pole, including safe use practices (updated 2024)   |
| <i>Updated Standards of the International Society for Terrain-Vehicle Systems</i> [7] | Set of standards for terminology and testing for modern day research on off-road mobility (updated 2020)                           |

### 3.1.3 General recommendations and lessons learned

The International Society of Terrain-Vehicle Systems defines drawbar pull as “the force, produced by the vehicle at the drawbar or hitch, available for external work, in a direction parallel to the horizontal surface over which the vehicle is moving” [7]. It is essentially the net traction that a tire or vehicle generates. During a drawbar pull test, a vehicle is driven with constant wheel velocity, and its forward motion is resisted by external force applied at its hitch. In addition to the imposed force, the vehicle must generate sufficient thrust to overcome rolling resistance. A schematic of the forces and moments acting on a 4-wheeled vehicle during a drawbar pull test is shown in Figure 2.

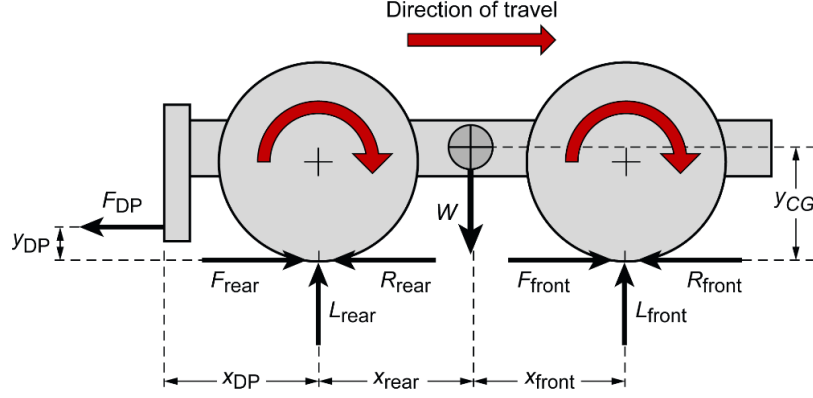


Figure 2: Forces and moments on a 4-wheeled vehicle during a drawbar pull test.

In this schematic,  $F$  is a force in the direction of travel,  $L$  is the normal load,  $R$  is a resistance force,  $x$  is a horizontal distance,  $y$  is the height of the applied external load, and  $W$  is the weight of the vehicle. The subscripts designate the rear and front of the vehicle, while CG stands for center of gravity and DP stands for drawbar pull. Thus, the drawbar pull force can be represented by Equation (1), assuming the front and rear axles are defined by a pair of wheels with identical driving conditions.

$$F_{DP} = \sum F_{axles} - \sum R_{axles} - ma \quad (1)$$

Drawbar pull is often normalized by the vehicle weight ( $W$ ) to produce a unitless value called drawbar pull coefficient ( $DP/W$ ). The drawbar pull coefficient can be evaluated with respect to various performance metrics such as slip, travel reduction, sinkage, and power number. These are discussed briefly below but are covered in more details in [6].

*Slip,  $i$ .* Slip is defined as “the relative motion between a traction element (ex. wheel) and the supporting surface” [7]. In the case of a wheel driving in granular soil, it is measured at the location where soil displacement occurs, which is typically below the surface (the top layer of soil moves with the wheel). Though the term “wheel slip” is commonly used when assessing vehicle performance, it is quite difficult to measure directly, especially when conducting full vehicle tests. Equation (2) provides the mathematical expression for wheel slip,  $i$ , where  $r_r$  is the effective radius of the wheel,  $\omega$  is the rotational velocity of the wheel, and  $v$  is the actual velocity of the wheel or vehicle. Because the soil shearing occurs below the surface, and because compliant tires have variable radii depending on the load and tire deflection, the effective radius is different from the geometric radius, and is dependent on load and soil conditions. The true effective radius can be measured by producing a zero-slip state in the same terrain conditions; however, this process is not trivial. For a 4-wheeled vehicle, it is also possible that each tire is undergoing different slip simultaneously.

$$i = \frac{r_r \omega - v}{r_r \omega} \times 100\% \quad (2)$$

*Travel Reduction, TR.* Travel reduction is associated with the test vehicle and is used to observe changes in forward progress as slip occurs. The zero-condition is not based on a specific physical phenomenon. Instead, it is based on a repeatable experimental condition such as driving in a self-propelled condition, where the drawbar pull force is equal to zero, on hard ground or on the test terrain. While, travel reduction may not be mapped to a specific terrain condition, it lends itself to easy comparisons between results from different laboratories. Travel reduction results must always be interpreted as relative to whatever zero-condition has been selected. Equation (3) provides the mathematical expression for travel reduction,  $TR$ , where  $v_{ref}$  is the measured velocity under the reference condition. An example plot of drawbar pull coefficient vs. travel reduction in soft soil is shown in Figure 3.

$$TR = \frac{v_{ref} - v}{v_{ref}} \times 100\% \quad (3)$$

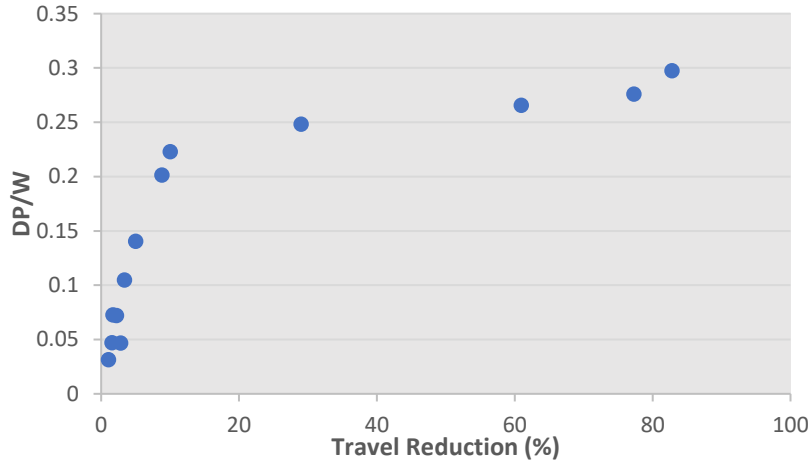


Figure 3: Sample plot of travel reduction vs. drawbar pull coefficient (DP/W)

*Sinkage, z.* Sinkage is a measure of the wheel's depth below the terrain surface. It is an excellent indicator of a vehicle's risk of immobilization; however, it can sometimes be difficult to measure directly. With rigid wheels, sinkage can be found by measuring the change in vertical height of a wheel axle or center. This is not the case for compliant tires though as tire deflection needs to be taken in to account. Rut depth can also be measured after the test, but at high slip conditions, these will get partially backfilled by soil.

*Power number, PN.* Power number is a unitless metric intended to quantify the power and energy costs of mobility. It is defined as the power being normalized by the vehicle's weight and velocity [8]. Equation (4) shows two ways to calculate PN. The first method is useful to calculating instantaneous PN and uses power,  $P$ , and velocity,  $v$ . To calculate an average PN over a traverse, it can alternatively be calculated by using energy,  $E$ , and total travel distance,  $d$  [9]. An example of DP/W vs. PN data is shown in Figure 4.

$$PN = \frac{P}{Wv} = \frac{E}{Wd} \quad (4)$$

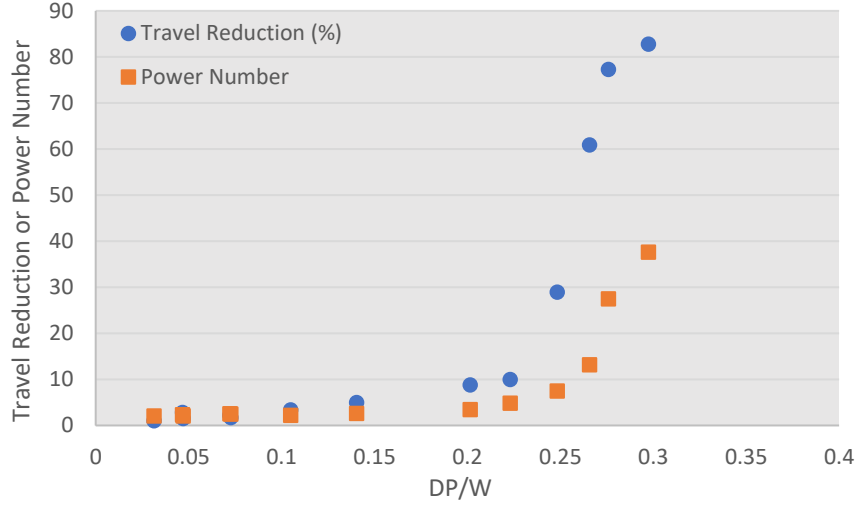


Figure 4: Sample plot of drawbar pull coefficient,  $DP/W$ , vs. travel reduction and power number

*Tractive efficiency,  $\eta$ .* Tractive efficiency is another unitless metric which represents the efficiency of transferring power to move an external load. It is defined as the ratio of the drawbar pull force and travel velocity to the vehicle power, Equation (5). As seen in Figure 5, this metric can be useful to understanding the most efficient driving conditions.

$$\eta = F_{DP}v/P \quad (5)$$

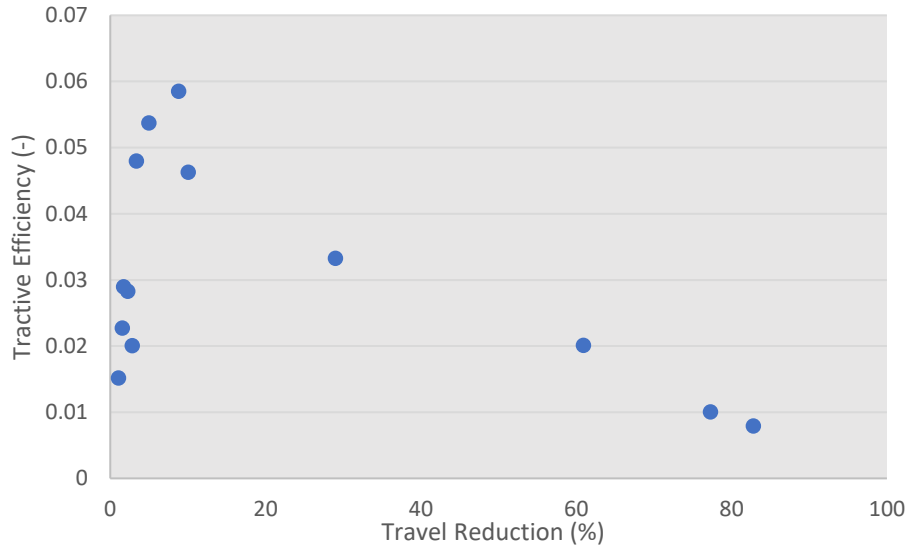


Figure 5: Sample plot of travel reduction vs. tractive efficiency

When using drawbar pull and its associated metrics to evaluate the performance of a vehicle, it is imperative that the terrain be as representative as possible of the actual operating environment. Discussions on terrain preparation in [6] are mostly specific to GRC-1 [10], a lunar mechanical simulant developed for mobility tests. GRC-1 is based on cone penetrometer data collected during the Apollo surface missions, with a bias towards the conservative end (low-strength) of the measured range. Procedures are provided to produce three distinct bulk density conditions with this material, though the procedures and lessons learned [6] can apply to other terrain types as well. Below are a couple of key points that are universal to terrain preparation for drawbar pull tests:

- It is critical to prepare the soil consistently between each test. This typically consists of loosening the soil to erase the stress history, compacting it to a desired density (if necessary), and leveling it to ensure a flat surface. The loosening step is of utmost importance as the vehicle will typically compact soil after driving on it. This can be done by either removing and carefully replacing the soil (not feasible for large-scale tests), or by “fluffing” up. At GRC, the soil is loosened with hand shovels (specific methods outlined in [6]), but it could also be loosened with tines or by fluidizing the soil with bursts of air. There are also a variety of ways to compact the soil including hand tampers, rollers, and induced vibrations. It is important to ensure that whichever method is utilized will produce consistent results. During both loosening and compaction, it is imperative to take care so as not to cause segregation of the simulant particle sizes.
- The cone penetrometer is a common tool used within the field of terramechanics to assess the relative strength of soil [11]. It is essentially a standard cone on the end of a shaft that is driven into the soil to collect pressure vs. sinkage data. From this data, a “cone index gradient”,  $G$ , can be calculated (see Figure 6). Though this gradient does not provide direct measurements of geotechnical properties such as friction angle and cohesion, it is good for quantifying the state of a terrain, which in turn can be used for 1) correlation to laboratory



measurements, 2) general assessment of the soil's relative strength, and 3) verification of a terrain preparation method. At GRC, laboratory tests were conducted on GRC-1 at various bulk density conditions, while cone penetrometer readings were collected for each. Thus, the cone penetrometer data collected during drawbar pull testing can be used to infer the geotechnical properties of the soil for a given test. It is also an effective tool to check for consistency between preparations. Reference [6] provides specific information on how the cone penetrometer data is used at GRC to correlate to specific terrain conditions.

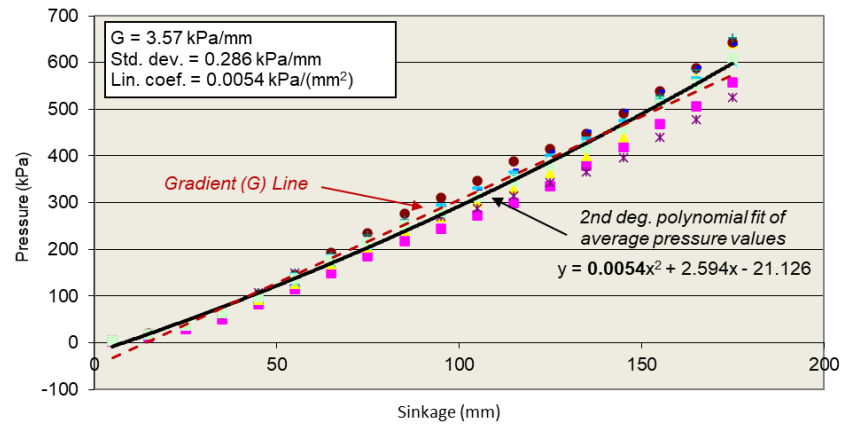


Figure 6: Example of cone penetrometer results taken for a semi-compacted GRC-1 state. In the plot eight data sets are shown together, along with a second-degree polynomial fit of the averages and the cone index gradient (G).

- It is also important to minimize the effects of boundary conditions due to the size of the soil bin. This can be done based on the pressure bulb theory [12] which allows for estimations of stress throughout the subsurface of a soil, due to surface pressure. A traditionally used rule of thumb states that the soil bin depth and width should not be less than five times the size of the wheel's greatest contact dimensions [12]. However, this does not apply to all situations.

The drawbar pull paper [6] also goes into detail on sensitivity studies performed on test parameters. The key takeaways are listed below:

- Several different bulk density conditions were produced at GRC. It was determined that the loosest one (where no compaction step was added) produced the most repeatable condition, and also the least amount of variation in vehicle performance from test to test. Because this was also the most challenging condition, it was selected as the baseline and has been used for most vehicle drawbar pull testing at GRC to date.
- At GRC, the drawbar pull force is applied via a drawbar pull rig (see Figure 7). This rig feeds out a cable, which is attached at a hitch point on the vehicle and applies controlled pull forces via changes in cable tension. It uses feedback from a load cell at the hitch to adjust the cable tension by varying the torque on a drum that the cable is wrapped around. Drawbar pull force can also be applied using a system of deadweights and pulleys, or with a sled.

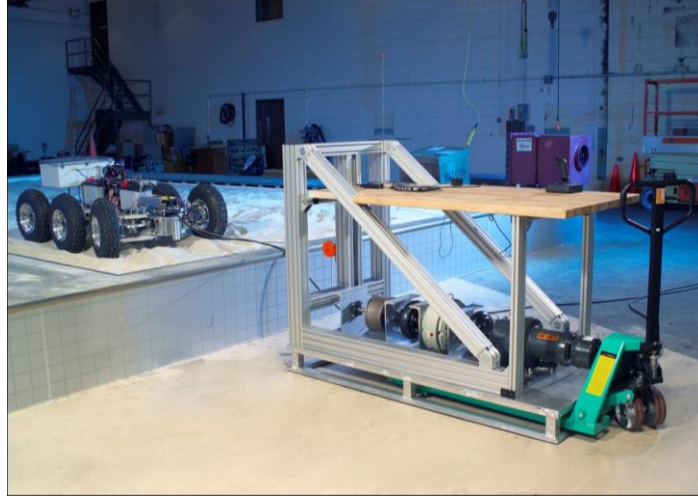


Figure 7: GRC Drawbar Pull Rig

- Typically, the drawbar pull force is applied in steps, such that a meaningful amount of performance data can be collected under each drawbar pull condition. The forces can be ramped up continuously but that can introduce acceleration forces, since the vehicle's speed will change with each drawbar pull force. It is important to ensure that these acceleration and dynamic forces are not included in the final data analysis since they are not representative of the true driving condition. It is important that the vehicle achieves a steady-state condition for each loading case before data is used. This can be identified by looking for areas where the vehicle speed remains constant.
- The location of the hitch point also makes a difference in the overall performance. If the intent is to simulate the vehicle towing a load (such as a trailer), then it is best to attach the cable at the same location used for towing. However, most of the time the drawbar pull test is intended to mimic other external forces acting on a rover, such as gravity when driving uphill. To minimize the moment on the wheels, it is best to attach the cable as close to the ground as possible, keeping in mind that that vehicle will likely sink during the test.

It should be noted that there are two key differences between a full vehicle drawbar pull test and a single-wheel drawbar pull test (addressed in Section 4.1). First off, most single-wheel tests are slip controlled (rather than force controlled), primarily due to limitations of the test rig. This can produce slightly different results. For example, a wheel with grousers may produce periodic changes in vehicle speed under a load-controlled test because the wheel's effective radius is greater at the grouser than at the rim ( $v = r_r \omega$ ). During a speed-controlled test, the linear speed is held constant so the wheel-soil response may be somewhat unrealistic. Also, the full vehicle tests take in to account the effects of the full mobility system (suspension, wheel spacing, wheel camber, etc.).

#### 3.1.4 Identified gaps in knowledge

It is important to note that without complete replication of the terrain conditions on the Moon and Mars, drawbar pull tests can only be used to characterize the performance of a vehicle – not predict

the performance of the vehicle. Also, the focus on large fast-moving vehicles, such as LTV, presents new challenges too. Below are the key gaps associated with full vehicle drawbar pull testing. Since many of these gaps apply across multiple areas, they are identified here merely by title. For more detail on each gap please refer back to Table 2 in Section 2.2.

1. *Unknown terrain conditions at the lunar south pole.*
2. *Effect of gravity on regolith and simulants.* [5]
3. *Inertial/dynamic effects during tire-terrain interaction testing.*

### 3.2 Slope Performance

Since slope traversal is often the driving case for traction related requirements, conducting vehicle tests on a slope can be the best way to assess the vehicle’s performance directly. This includes driving up-slope, down-slope, and cross-slope. Performing tests with the full vehicle (or locomotion subsystem) on an incline also allows for system-level factors (such as center of gravity height, shift in weight, or suspension response) to come into play, which is lacking from single-wheel traction tests, and sometimes even full vehicle drawbar pull tests. This is often a great way to assess the traction capability of a rover since it is the closest to the actual driving conditions.

#### 3.2.1 Applicable resources

Though the “Drawbar Pull Procedures for Off-Road Vehicle Testing” paper does not specifically address slope climbing tests, much of the guidance, such as terrain preparation, is similar. Table 4 lists the recommended resources related to slope testing.

Table 4: Recommended resources related to slope testing

| Reference                                                                             | Description                                                                                                                        |
|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| <i>Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing</i> [6]                  | Detailed description of drawbar pull test procedures utilized at NASA GRC, including discussions on theory and terrain preparation |
| <i>Lunar Regolith Simulant User’s Guide: Revision A</i> [4]                           | NASA guide on known mineralogical lunar regolith simulants for the lunar south pole, including safe use practices (updated 2024)   |
| <i>Updated Standards of the International Society for Terrain-Vehicle Systems</i> [7] | Set of standards for terminology and testing for modern day research on off-road mobility (updated 2020)                           |

#### 3.2.2 General recommendations and lessons learned

The following metrics are recommended for slope-climbing tests. Many of these are the same as discussed in Section 3.1 and thus the descriptions here are not as detailed.

*Incline (or slope) angle.* Because vehicle performance is highly sensitive to slope angle, it is important that this be measured accurately. However, this is not always trivial since the soil may have a slight difference in overall angle than the tilt-bed frame, and there may also exist local variations in the soil bed incline angle. It is best to minimize these variations during the terrain preparation. The mean incline angle can then be measured

through a variety of means such as with an inclinometer or by using motion tracking equipment to create a virtual plane of the tilt-bed using stationary markers. Another option, which is more accurate but tedious, is to map out the terrain using visual methods, such as stereo cameras or light detection and ranging (LiDAR) and calculate either local or global incline angles. Because performance is so sensitive to incline angle, it is best to drive on a number of incline angles, especially in the middle range of slip or TR where there is often a bend in the slope angle vs. TR curve. In the example shown in Figure 8, this occurs around 20 degrees.

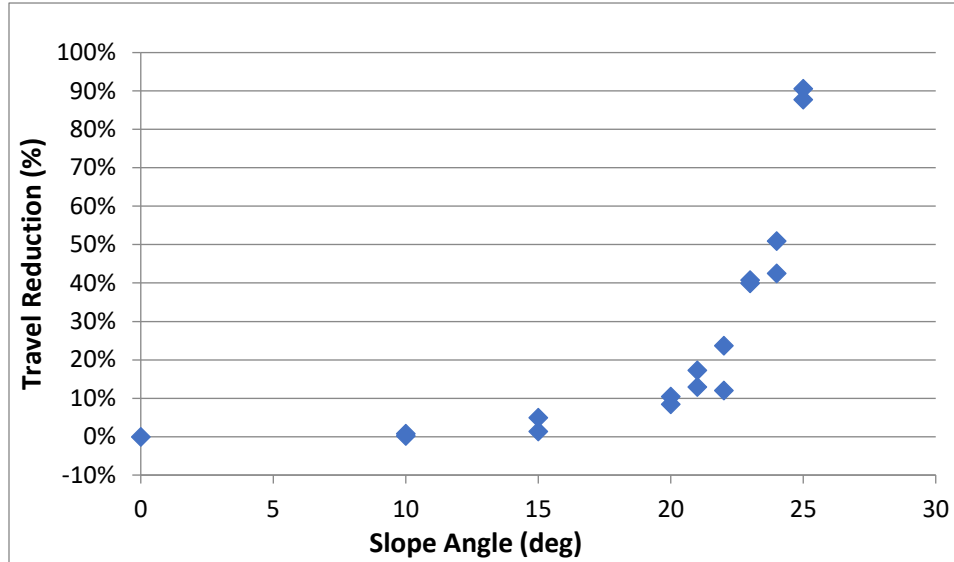


Figure 8: Sample slope vs. travel reduction plot.

*Wheel slip,  $i$ , or travel reduction, TR.* Travel reduction is preferred based on the reasons presented earlier in the paper; however, either term can be used if the method of defining a reference speed (or effective radius) is provided. One key thing to note here is that the true vehicle velocity should be calculated along the plane of the tilt-bed, and in the *intended drive direction* of the vehicle. This becomes a bit more complex when driving across slope, since the vehicle will experience lateral slip (see Figure 9).

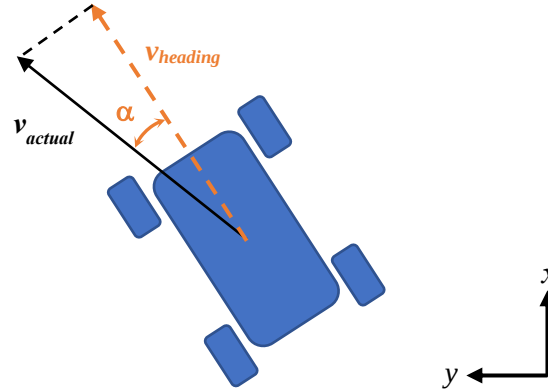


Figure 9: Diagram of rover driving up-slope (x-direction) and cross-slope (y-direction).  $v_{actual}$  represents the true vector of vehicle velocity due to side slip;  $v_{heading}$  represents the component of velocity in the intended drive direction;  $\alpha$  represents slip angle.

*Slip angle,  $\alpha$ , or sideslip.* Slip angle is the angle formed between the wheel/vehicle travel and the line of intersection of the center plane of the tire or wheel/vehicle with the supporting surface [13]. It is represented by  $\alpha$  in Figure 9. Sideslip can also be used, which is slip in the lateral direction, in general characterized by the tangent of the slip angle [7]. It is recommended to use one of these metrics when conducting tests on a slope for cases where at least a portion of the vehicle's travel is in the cross-slope direction since gravity will typically force lateral movement. Though slip angle and sideslip are not as indicative of vehicle entrapment, they are great metrics for assessing travel efficiency.

*Sinkage,  $z$ .* Sinkage is much more difficult to quantify during slope-climbing tests since the ground surface is not level. Sinkage needs to be measured normal to the plane of the terrain. One approach that has been taken at GRC was to produce a virtual point cloud of the terrain using structured light and photogrammetry and calculating the relative position between wheel center and the closest terrain point to estimate sinkage [14].

*Power number,  $PN$ .* Power number is an especially useful metric for these tests because it provides useful information related to drive efficiency, whereas travel reduction and sinkage are intended to assess the vehicle's maximum tractive potential and risk of entrapment. Sometimes there is a tradeoff between drive efficiency and maximum tractive potential so this metric can be very important depending on the specific test objectives.

Such as with drawbar pull tests, terrain preparation is key to obtaining meaningful results. The same preparation techniques presented in Section 3.1 can be applied here. However, this can be a challenge depending on the incline type. At the NASA GRC SLOPE Lab, an adjustable inclined soil bed is used. It can be raised to set positions from 0-45° using a pair of hydraulic lifts. In this case, the terrain can be prepared while the bed is flat, and then lifted into place. In other situations, the incline may either be a permanent fixture or a hill that must be graded manually. This is not ideal because it is very difficult to create the same soil condition each time. Also, soil tends to

shift downhill overtime, thus the incline angle may not be the same from test to test and would need to constantly be re-graded.

Also, just as with drawbar pull testing, the vehicle must travel enough distance such that it reaches a steady-state condition. This is where there is minimal difference in incline angle and vehicle speed. Typically, there are changes in speed as the vehicle begins its operation, due to the acceleration forces and for the initial sinkage of the wheels. A rough “rule of thumb” is that it takes about one wheelbase length to reach steady state (this assumes that the rear tires are now driving in the ruts of the front tires); however, this varies between test conditions. It's best to run some checkout tests first to identify trends.

Because slope traversal tests are a great way to assess the full system's performance, it's critical that the locomotion configuration is as close to the actual driving configuration as possible. This starts with the weight-on-wheels. The performance of the wheels is dependent on load; thus, the test platform should be designed such that the force between the wheels and terrain matches what is expected on the Moon or Mars, or at least produces a conservative condition. This can be done via an off-loader or by using a test platform that matches the equivalent weight of the lunar or Martian rover (the latter approach is what is typically used by NASA). It's also important to ensure that configurations such as wheel spacing, center of gravity location, suspension stiffness, etc. are all accurate since they each have an impact on performance when traversing slopes.

It's important to note that the above recommendation for matching tire loads is assuming *quasi-static* driving conditions. In other words, these test methods assume that forces due to inertia and acceleration are negligible. Because the test vehicle mass is much lower than the mass on the Moon or Mars, the forces due to inertia and acceleration in the lab are not representative of what would be expected on the flight vehicle. For slow moving rovers, this is typically not a problem. However, for faster moving vehicles, such as LTV, this is something that must be considered when devising test plans. There likely are dynamic effects that cannot be simulated in a laboratory.

### 3.2.3 Identified gaps in knowledge

Since many of these gaps apply across multiple areas, they are identified here merely by title. For more details on each gap please refer back to Table 2 in Section 2.2.

1. *Inertial/dynamic effects during tire-terrain interaction testing.*
2. *Effect of gravity on regolith and simulants.*
3. *Unknown terrain conditions at the lunar south pole.*

## 3.3 Obstacle Traversal

Though tire endurance testing is often conducted at the component level, the ability of a vehicle to traverse obstacles is often better assessed at the system level. For one, tires only play a part in a vehicle's ability to climb rocks and other terrain features; suspension, drive train, control algorithms, and weight distribution all have an impact. Secondly, it is very difficult to produce a true “self-propelled” state through single-wheel testing.

Obstacle traversal encompasses a wide range of terrain features including, but not limited to rocks, craters, ledges, and potentially even obstacles encountered during egress from a lander. System-level obstacle testing can have several objectives. A couple of examples are verifying the ability of the rover to meet tractive performance goals, estimating power needs for various operations, and evaluating control or software algorithms related to vehicle navigation and/or stabilization.

### *3.3.1 Applicable resources*

The authors are unaware of any existing resources which focus on test methods specifically for evaluating obstacle traversal.

### *3.3.2 General recommendations and lessons learned*

Rocks typically present the most challenging, or at least most common, obstacle traversal challenge. Surface vehicles and orbiters can only detect rocks down to a certain size, and there are often not viable options to avoid some rocks. For large rocks, a vehicle's qualifier for success is usually binary; can it traverse the rock or not. In the case of LTV, the rover is required to traverse rocks up to 30 cm in height. Because the requirement does not specify the rock shape or orientation, and because it is often not known, it is important to test the system over a range of conditions that bound the challenge. For example, a completely vertical rock face that is featureless is much harder to traverse than a rock of the same size that has a more gradual surface with many features for the tires to engage with. The method by which the rock is fixed to the ground makes a great difference as well. Typically, loose rocks that are laid on top of soil are easier to traverse than ones that are fixed and do not give way. For example, during qualification testing for the VIPER rover program [15], a mobility test platform was driven over various rocks 20 cm in height on an incline. In some cases, the vehicle traversed the rock easily while in others it was unsuccessful. The vehicle's success was highly dependent on the shape and orientation of the rock. Figure 10 shows an example where the VIPER test vehicle was attempting to traverse 20 cm tall rocks on an incline. In the top image, the rock was not embedded in the sand and was oriented such that the face contacting the wheel had a gradual slope. In this case the vehicle traversed the rock easily. In the bottom image, the rock was embedded in the sand and positioned such that the contact face was nearly vertical. During this test the rear wheel was unable to traverse the rock.

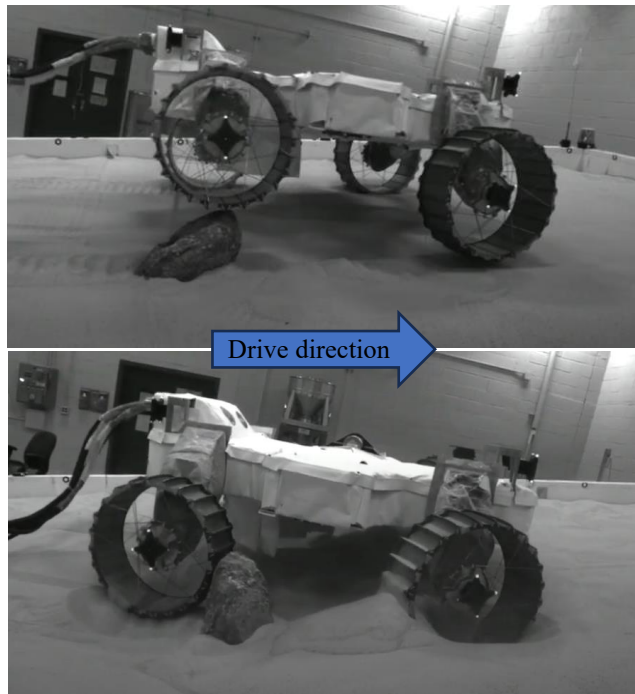


Figure 10: VIPER test platform attempting to traverse 20 cm tall rocks of different orientations. In both images the rover is driving to the right and the rear wheels are attempting to climb the rock. Top image shows a successful traverse; bottom image shows an unsuccessful traverse.

Craters also present a major mobility challenge for roving vehicles. There exists two types of challenges related to craters: one where the crater is so large that all four wheels are on the crater wall at the same time and it becomes more of a slope-traversal case; and one where the craters act as negative features and one or two wheels at a time must pass through without getting stuck. The latter case is worth investigating in a similar manner to the rock traversal testing mentioned above. The size and shape of these smaller craters have a big impact on performance; thus, it is important to account for the potential bounding cases.

For both positive and negative obstacles, the soil condition used for testing is critical. In the case of rock traversal, the ability of the tire and the mobility system to “grab” on to the rock and not break free is important, but so is the ability of the other tires to generate enough thrust in the soil to help push that tire over the rock. When traversing craters, just as with slope-climbing tests, it is important to match the soil condition to the actual mission surface as best possible, or at least produce a conservative case. The methods of terrain preparation discussed in Section 3.1 and [6] are applicable here as well.

Often a “pass/fail” metric is used to assess obstacle traversal performance, depending on the objective of the tests. However, other performance related metrics, such as the ones discussed in Section 3.1 and [6], can be helpful.

There are situations where conducting system or vehicle tests on a field of various obstacles is useful, not necessarily just obstacles that present mobility challenges. Other rover-related



objectives, such as maintaining bearing with a tracking system, quantifying the effective travel velocity of a rover, or ensuring minimal shock on the system, can be evaluated by driving through an array of rocks and craters. For these tests it's more important to identify the appropriate distribution of obstacles sizes based on known or predicted surface data. For example, the Mars rover program uses a metric called “cumulative fractional area” (or CFA) to define the rock size-frequency distribution for landing or operating sites [16]. This information is then used to create test terrains for rover testing. Though these terrain cases don't always have large rocks that represent major mobility challenges, they are useful for assessing other mobility-related objectives as discussed above.

### 3.3.3 Identified gaps in knowledge

Since many of these gaps apply across multiple areas, they are identified here merely by title. For more details on each gap please refer back to Table 2 in Section 2.2.

1. *Inertial/dynamic effects during tire-terrain interaction testing.*

## 4 SINGLE WHEEL TESTS

### 4.1 Drawbar Pull / Traction

#### 4.1.1 Applicable resources

Table 5 contains recommended resources related to single-wheel drawbar pull testing. Note that these are the same resources mentioned in 3.1.2 but are applicable here as well.

Table 5: Recommended resources related to single-wheel drawbar pull testing

| Reference                                                                             | Description                                                                                                                        |
|---------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------|
| <i>Drawbar Pull (DP) Procedures for Off-Road Vehicle Testing</i> [6]                  | Detailed description of drawbar pull test procedures utilized at NASA GRC, including discussions on theory and terrain preparation |
| <i>Lunar Regolith Simulant User's Guide: Revision A</i> [4]                           | NASA guide on known mineralogical lunar regolith simulants for the lunar south pole, including safe use practices (updated 2024)   |
| <i>Updated Standards of the International Society for Terrain-Vehicle Systems</i> [7] | Set of standards for terminology and testing for modern day research on off-road mobility (updated 2020)                           |

#### 4.1.2 General recommendations and lessons learned

The tractive performance of a single wheel can be evaluated using a test rig termed a “single wheel dynamometer”. At NASA GRC this single wheel test rig is called TREC (Traction and Excavation Performance Capabilities), Figure 11. The TREC rig consists of three main features: 1) a linear carriage with motion along the x-axis, 2) a wheel and tire assembly with rotational motion, and 3) a linear carriage that the tire is mounted to with free-fall in the vertical direction. In addition, the TREC rig includes a load cell mounted at the wheel hub to measure the forces and moments and a

linear variable differential transformer (LVDT) to measure sinkage (though not deformation of a compliant tire). Similar to a full vehicle drawbar pull test, the single wheel test is used to evaluate the net traction that a tire generates. The wheel and linear carriage can be driven independently at speeds which cover a range of slip values from negative to positive (skidding to rotating in place, respectively). In contrast to full vehicle drawbar pull tests where the test is force controlled, the single wheel test is typically speed controlled such that the slip can be varied from test to test.

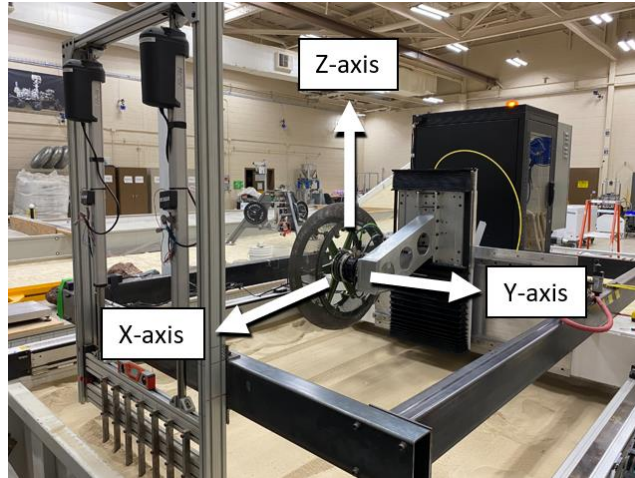


Figure 11. Single wheel TREC rig at NASA GRC.

A schematic of the forces and moments acting on a wheel during a single wheel tractive performance test is shown in Figure 12.

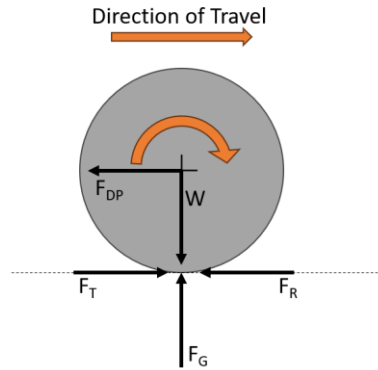


Figure 12. Forces and moments acting on a wheel during a single wheel tractive performance test.

In this schematic,  $F_T$  is a force in the direction of travel,  $F_G$  is the ground force,  $F_R$  is the resistance force, and  $W$  is the weight on the wheel. Thus, the drawbar pull force ( $F_{DP}$ ) can be represented by the Equation (6).

$$F_{DP} = F_T - F_R \quad (6)$$

Again, drawbar pull is normalized by the vehicle weight ( $W$ ) to produce a unitless value called drawbar pull coefficient ( $DP/W$ ). For a single wheel test, the drawbar pull coefficient is commonly evaluated with respect to various similar performance metrics such as slip, sinkage, slope potential and power number. These are discussed briefly below.

*Slip,  $i$ .* Wheel slip is slightly easier to quantify at the single-wheel level than at the full vehicle level since slip can vary from wheel to wheel. However, defining an effective radius is still important. Ideally, the tire would be driven over the test terrain and the point at which no shear displacement is observed is set as the zero-slip condition. As previously stated, this process is quite subjective, and the zero condition can vary for compliant tires under different loading and terrain conditions. An example of the soil motion below the surface, and complicated even further by the addition of grousers, is shown in Figure 13.

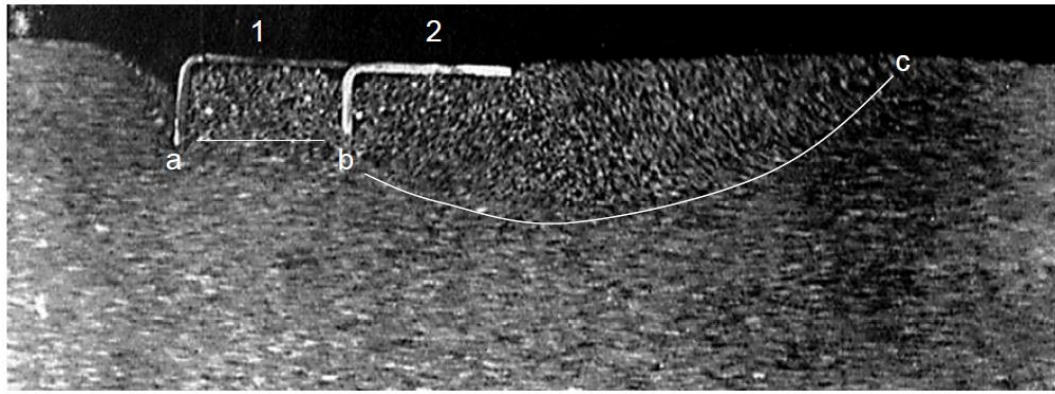


Figure 13. Extended exposure photograph showing the action of soil underneath adjacent and spaced cleats. Local failure occurred along surface a to b and general failure occurred along surface b to c.

Original work performed by Dr. M.G. Bekker (Bekker 1960). From [17].

*Sinkage,  $z$ .* Sinkage remains the same as for full vehicle drawbar pull testing. On TREC, the LVDT is used to measure the vertical displacement of the linear carriage. The deflection of compliant tires remains an issue but could be estimated based on quasi-static stiffness curves when loaded against a rigid plate. However, this is only an approximation, as the amount of tire deflection under load will be different in compressible soil versus a non-compressible hard surface.

*Slope potential,  $SP$ .* The slope potential is a metric used to quantify the potential climbing capability of the wheel in the same soil. Equation (7) is an empirically derived equation commonly used to estimate slope potential, though this is only an approximation and is dependent on vehicle kinematics.

$$SP = \tan^{-1} \left( \frac{DP}{W} \right) \quad (7)$$

*Power number; PN.* Power number for a single wheel is no different than the power number defined for the full vehicle. In the case of the TREC rig, torque is used to determine the power number, Equation (8). Here,  $\tau$  is the wheel torque measured at the hub,  $W$  is the wheel weight, and  $v$  is the forward velocity.

$$PN = \frac{P}{Wv} = \frac{\tau\omega}{Wv} \text{ or } PN = \frac{E}{Wd} \quad (8)$$

The same recommendations for simulant selection, terrain preparation, and verification are suggested for single wheel drawbar pull tests as for full vehicle tests; refer to Section 3.1.3 for the full discussion. For TREC, testing is usually done with the simulant in a loose condition. It is prepared by using two passes with a rake that extend approximately 18 cm below the surface of the soil and two passes with a level. In theory, the rake tines should extend further below the soil surface to reduce boundary conditions, but for lunar applications it can be argued that the first 10's of centimeters of the lunar surface consist of loose material with more compacted material underlying [18].

#### 4.1.3 Identified risk and gaps in knowledge

Below are the key gaps associated with single-wheel drawbar pull testing. Since many of these gaps apply across multiple areas, they are identified here merely by title. For more detail on each gap please refer back to Table 2 in Section 2.2.

1. ***Unknown terrain conditions at the lunar south pole.***
2. ***Effect of gravity on regolith and simulants.*** [5]
3. ***Inertial/dynamic effects during tire-terrain interaction testing.***

## 4.2 Endurance Related Tests

Endurance related tests ensure that a tire will be able to operate in the desired environment for the desired length of time without succumbing to any type of failure (e.g., yield, fatigue, fracture, etc.) that compromises the ability of the tire to meet requirements. Typically, endurance related tests in space flight applications aim to demonstrate from two to four times life (Source for 4x: [19] §2.4.2.1; [20] §7.3; [21] §4.19.3.2; Source for 2x: [21] §4.19.3.3—if no loss of life possible) with one life equating to the planned mission distance (from manufacture to end of mission).

### 4.2.1 Applicable resources

Below are available resources for developing test programs related to tire endurance. It's important to note that the NASA standards and requirement documents on this list may not apply to all missions. It is up to the user to identify and follow the appropriate standards that are being levied on the tires for their specific mission.

Table 6: Recommended resources related to endurance testing (note: NASA standards or requirements mentioned here should not supersede or replace standards levied by a given mission program)

| Reference                                                                                     | Description                                                                                                                                                                                                                                                                                                                                                                                                                    |
|-----------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>Design and Development Requirements for Mechanisms, NASA-STD-5017B</i> [21]                | Standard establishing common NASA design, development, and test requirements for mechanisms whose operation is required for safety or mission success.                                                                                                                                                                                                                                                                         |
| <i>General Environmental Verification Standard (GEVS), GSFC-STD-7000A</i> [19]                | Standard providing requirements and guidelines for environmental verification programs for Goddard Space Flight Center (GSFC) payloads, subsystems and components and describes methods for implementing those requirements. It contains a baseline for demonstrating by test or analysis the satisfactory performance of hardware in the expected mission environments, and that minimum workmanship standards have been met. |
| <i>Fracture Control Requirements for Spaceflight Hardware, NASA-STD-5019A w/Change 1</i> [20] | Fracture control is implemented to reduce the risk of a catastrophic failure from a defect or damage. The intent of this standard is to provide fracture control requirements for spaceflight hardware.                                                                                                                                                                                                                        |

#### 4.2.2 General recommendations and lessons learned

Endurance tests need to include environments and loads that are representative or bounding of what will be seen over the course of the hardware's life. For tires these environments include atmospheric and terrain considerations (e.g., temperature, slopes, obstacles/reliefs, dust/regolith, vacuum, radiation, etc.). These environments can impose loads directly or in combination with rover operation. For instance, the structural loads and wear a tire sees can be greatly impacted by the speed and angle at which it encounters obstacles, the cumulative distance traveled, slopes and relevant attack angle, turning, thermal loads, launch vibration, the suspension system, actuator driven blocked loads, and others (e.g., stowage, EDL, etc.). These conditions invariably induce loads in and about the radial, lateral, and longitudinal directions in various combinations. It is important to understand and accurately account for these in endurance related tests.

Tires have some other unique considerations. For instance, distance traveled may be more than end to end travel when accounting for things like slip. This should be considered when setting the total distance requirements for verification and validation testing. Additionally, it is of primary importance to use a realistic number and size of obstacles as part of the endurance testing and encounter them at relevant speeds and intervals [16]. Failure to properly account for this in testing can lead to unanticipated damage to the tire. An example of unanticipated damage occurred on the Mars Curiosity Rover as shown in Figure 14 [22]. This led to a change in approach on future rovers as part of Mars Sample Return (specifically Perseverance and other follow-on rovers). In each instance early breadboard vehicle scale tests were done on conservative representative terrain

and wheel load data collected in all directions. This data provided a load profile to which single tire endurance tests could attempt to be tuned.

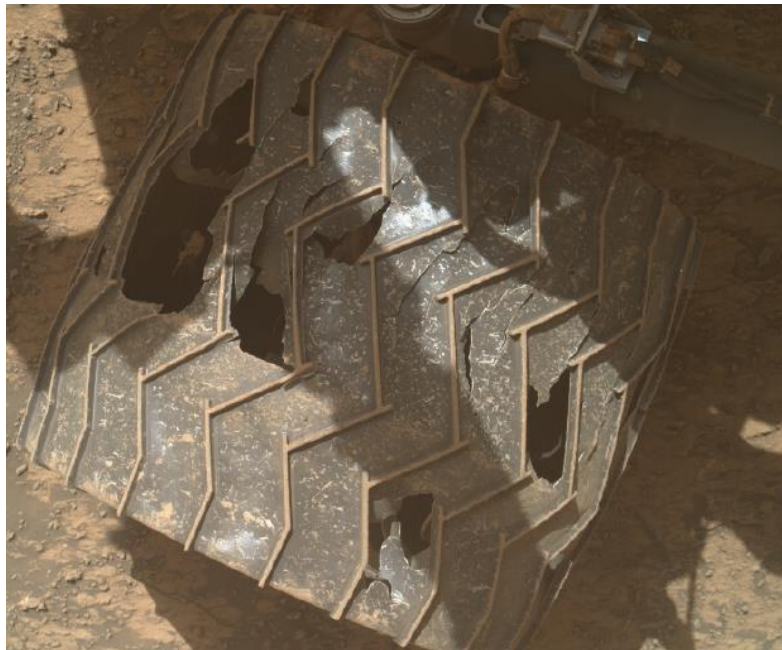


Figure 14. Image of damage to Mars Curiosity wheel. Credit NASA/JPL-Caltech.

Thermal loads include both survivability at the extremes and survivability through thermal cycles. The impacts to the tire can come from the temperatures alone, thermally induced stress, and impacts on material strengths. For verification and validation endurance tests, NASA-STD-5017 recommends testing to the equivalent number of thermal cycles expected over the service life [21]. For longer duration missions that may experience hundreds to thousands of sols or sun cycles it may be impractical to test to the equivalent number of cycles. In these instances, an accelerated endurance test in combination with other testing and analysis would likely be necessary to fulfill verification and validation requirements. However, it is important to consider the material of the tire, since accelerated endurance tests may not be possible or realistic for strain dependent materials.

Endurance testing should be performed at the tire level but can, in addition, be performed at a subsystem or component level. Currently, there is no known single test rig which can evaluate all the requirements (temperature, slopes, obstacles/reliefs, dust/regolith, vacuum, radiation, etc.) of a rover wheel or mobility system at once - it is unlikely a system like this will even exist in the near future. This is where foresight needs to be put into the testing program. It is often beneficial to perform testing on subassemblies, or individual components of the tire - for example on unique geometry (e.g., springs), unique materials, and for wear and fatigue. In these examples, testing on individual samples can uncover issues earlier in the design process and is simpler than requiring a full build.



NASA GRC has initiated a durability screening test campaign to evaluate SMAs and conventional materials that may be used for compliant rover tires. A commercial tribometer, the TRB3 from Anton Paar, has been acquired and commissioned (Figure 15). This tribometer is capable of continuous rotation as well as oscillating and linear wear with contact forces up to 60 N and 20 N of frictional force while recording real-time wear at a temperature range of +450°C (723K) to -100°C (173K). Discrete test points at lower temperatures can be achieved with direct cryogenic purge. The ultimate goal of this test campaign is to quantify primary wear couples and third body wear (from regolith or self-generated debris) and determine their contributing effect on durability and wear of off-road planetary tire materials. It is important to understand how specific tire designs wear out at contact points and flexures; and this rig will provide foundational data to anchor analytic life and durability calculations for tire designs. More importantly it is important to determine how the wear rates are affected by temperature, which has been shown to increase by orders of magnitude as you get colder [23].

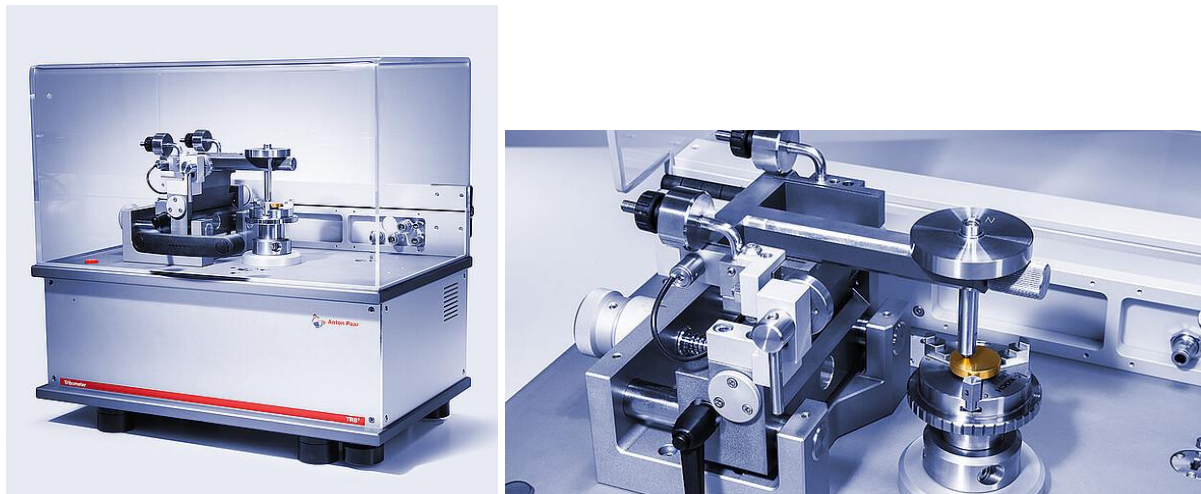


Figure 15: Commercial tribometer at GRC for testing primary wear couples and third body wear on material samples (credit: Anton Paar).

At NASA GRC there is another state of the art test rig under development, the Lunar Environment Strength Test Rig (LESTR), to allow sustained and cyclic tensile and bending tests of material samples at controlled temperatures of 40–125K (Figure 16). Though the rig was designed for stress-strain and fatigue testing of wire, it could potentially evaluate other sample shapes as well (e.g., dog bone).



Figure 16. Design concept for the Lunar Environment Strength Test Rig at NASA GRC.

At the tire level there is the Extreme Cyclic Environmental Load (XCEL) test rig (Figure 17). This rig allows for cyclic (currently 1 Hz at 2.54 cm displacement) radial compression tests over a wide temperature range (currently  $-143^{\circ}\text{C}$  (133K) to  $97^{\circ}\text{C}$  (370K)). Various interfaces can be used to compress the tire such as a flat plate (simulating highway-type terrain); a wedge-like obstacle (simulating rocks); and even a point load. The downfall to this rig is that it is not also in vacuum and thus cannot evaluate the thermal vacuum performance of a full tire. Alternately, if temperature is not a concern (or simply as an initial test), large distances and radial load can be imposed on a tire in a standard commercial tire drum rig or on a load frame rig with various interfaces (such as the aforementioned flat plate, wedge-like obstacle, or point load).





Figure 17. EXtreme Cyclic Environmental Load (XCEL) test rig at NASA GRC.

To evaluate against the effects of dust in vacuum, NASA GRC has a new test capability called the VOiD Chamber (Vacuum Operations in Dust Environment) (Figure 18). This test rig provides the capability to study sub-meter cubed experiments in simulated extraterrestrial environments. VOiD was designed to operate under thermal (93K to 423K) and vacuum control ( $10^{-6}$  torr) with regolith simulant in the chamber. The chamber offers four mounting points with up to 220 N load capacity and multiple auxiliary ports for customer designed experiments.

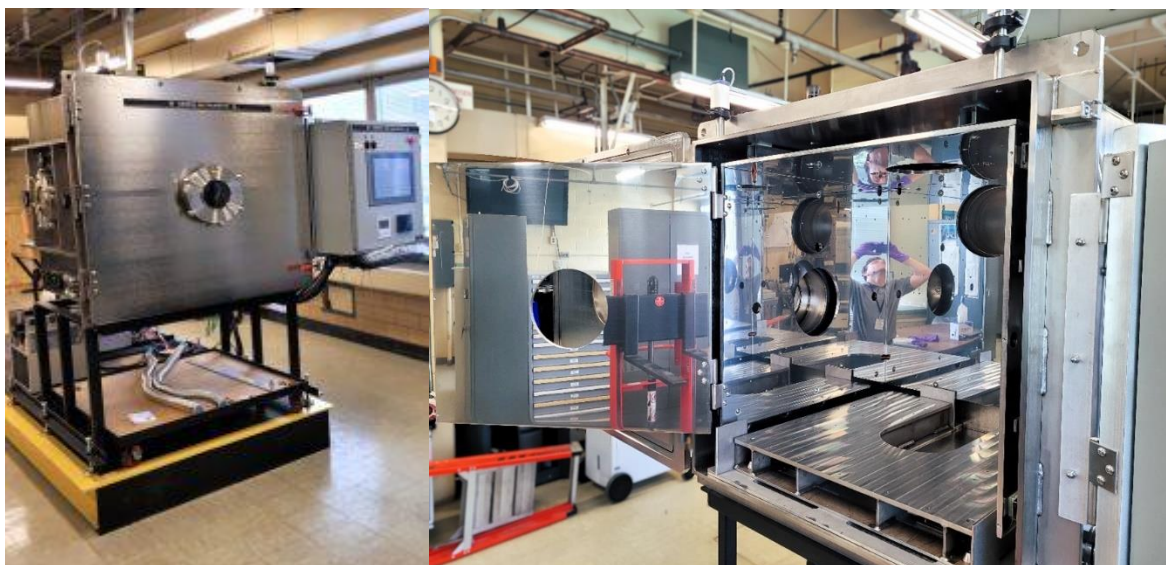


Figure 18. VOiD chamber at NASA GRC for the evaluation of subassemblies or components against thermal vacuum and dust.

To assess against realistic terrain and temperature, the EXtreme Terrain Endurance Rig (XTERra) at GRC is a record player-type rig (the tire is the needle on a rotating carousel) where the carousel and tire are independently driven (Figure 19). The rig can have combinations of soil and/or obstacles such as boulders or bedrock on the carousel, provide a temperature range (currently  $-130^{\circ}\text{C}$  (143K) to  $70^{\circ}\text{C}$  (343K)), impart direct vertical force and torque loads, indirect lateral loads (from the forced turning) and create forced slip conditions. If soil is included, a dusty environment can also be a natural (but uncontrolled) consequence. This rig has a couple of limitations. The constant turning makes it hard or impossible to match both vertical and lateral loads simultaneously. If the vertical loads are tuned to match the full-vehicle performance likely the resulting lateral loads will be excessive—larger tires exacerbate this effect. Also, the current setup does not incorporate the effects of a realistic suspension, this can lead to overly conservative dynamic loads being imparted on the wheel. Additionally, there is minimal variability in the terrain, meaning that every time the carousel completes one rotation, the tire drives over the same obstacles. This is not realistic of a true mission drive path and can be avoided by manually modifying the terrain-scape at predefined time or length of travel intervals. It should be noted that modifying the terrain-scape involves a lot of manual labor and slows the progress of the test. A rig capable of matching the loading conditions and drive path more precisely would prevent over or under loading a tire during test.



Figure 19. EXtreme Terrain Endurance Rig (XTERra) at NASA GRC shown with a bin of JSC-1A and volcanic rocks.

Another limitation with this type of test is that it was designed with the short duration missions of the past in mind. One could easily validate to 4x mission life if the length of the mission was only 4 km in distance traveled. For longer duration missions, such as LTV, which is slated to drive thousands of kilometers over a ten-year time frame, testing to 4x life at nominal speed could be impractical. It is likely that an accelerated version of this test or a combination of life testing with analysis may be necessary to verify and validate the performance requirements of rovers for long distance/duration missions. Again, caution should be used running accelerated tests when the tire material is strain dependent.

An example which included a realistic suspension system in the endurance-type test was JPL's use of a "pony walker"-style test rig (tires drive over a static terrain in a circle, tethered at the center) with half of the vehicle suspension system in-place for the Perseverance rover, Figure 20.



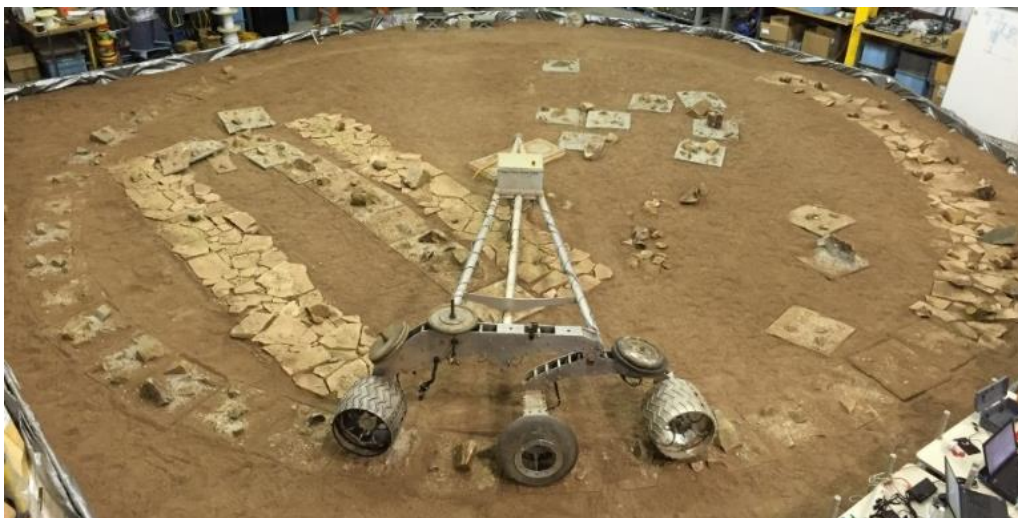


Figure 20. Photograph of JPL wheel life test rig. Credit NASA/JPL-Caltech.

Additionally, beyond just causing wear, thought should be given to the possibility and impact of regolith or rock intruding into and/or becoming trapped in a particular tire design as has been the case during the M2020 mission (Figure 21).



Figure 21. Photo of Mar's Perseverance rover with rock stuck in one of the wheels (credit NASA/JPL-Caltech).

To summarize, endurance testing should be done at the tire level but can be and realistically should be augmented at the subsystem or component level. Of primary importance is capturing a realistic

operational environment (in particular: obstacles, speed, temperatures, combined loading conditions, regolith, and service life).

#### 4.2.3 Identified gaps in knowledge

For more detail on each gap please refer back to Table 2 in Section 2.2.

1. *Challenge to performing standard life testing of tire or rover*
2. *Inertial/dynamic effects during tire-terrain interaction testing.*

A major lesson learned, discussed in more detail in Table 1 in 2.1, in doing endurance related tests is that:

1. *It is not feasible to evaluate all operating conditions with one test.*

### 4.3 General Characterization Tests

There are several characterization tests that are necessary to both understand and be able to model/predict the performance of the tire. Several have been mentioned already, such as tractive performance. Some additional characterization tests are required to round out the understanding of a given tire. These tests can take on greater importance for unique materials or for compliant tires where behavior can be more difficult to predict. These tests include (but are not necessarily limited to): friction, rolling resistance, stiffness, and vibration characterization.

#### 4.3.1 Applicable resources

Table 7: Recommended resources related to characterization testing (note: NASA standards or requirements mentioned here should not supersede or replace standards levied by a given mission program).

| Reference                                                                                       | Description                                                                                                                                                                                                                                                                                                                                                                                                                      |
|-------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>The Development and Characterization of the Shape Memory Alloy Spring Tire for Mars</i> [24] | The SMA Spring Tire was adapted for Martian rover applications with a focus on durability. Extensive work was performed to mature the SMA Spring Tire to a Technology Readiness Level (TRL) of 6 for the Martian environment. This paper summarizes the developmental work completed to date and presents key characterization data on two SMA Spring Tire point-designs.                                                        |
| <i>Force Limited Vibration Testing, NASA-HDBK-7004C</i> [25]                                    | This Handbook establishes a common framework for consistent practices across NASA programs. This third revision of the Handbook includes several advances in the calculation and application of vibration force limits, guidelines for the application of force limiting, and data from a third flight experiment that involved measuring the forces and accelerations at the interface between a spacecraft and launch vehicle. |

|                                                                                |                                                                                                                                                                                                                                                                                                                                                                                                           |
|--------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <i>General Environmental Verification Standard (GEVS), GSFC-STD-7000A [19]</i> | This standard provides requirements and guidelines for environmental verification programs for GSFC payloads, subsystems and components and describes methods for implementing those requirements. It contains a baseline for demonstrating by test or analysis the satisfactory performance of hardware in the expected mission environments, and that minimum workmanship standards have been met.      |
| <i>Load Analyses of Spacecraft and Payloads, NASA-STD-5002A</i>                | This NASA Technical Standard describes the accepted practices and requirements for the conduct of load analyses for payloads and spacecraft structures. Load regimes are identified. Requirements are set for establishing forcing functions and mathematical models and for performing analyses and verification of models by tests. Major methods of analyses, practices, and processes are identified. |

#### 4.3.2 General recommendations and lessons learned

*Friction test.* Frictional characterization is important to characterize performance on obstacles or during “highway” driving and is more critical for novel tire materials or designs. For a recent compliant spring tire developed at GRC various types of bedrock, assumed to be representative of the Martian terrain, were selected to evaluate the static and dynamic friction of the tire against the rock interface, Figure 22. NASA GRC Mars Spring Tire prototype in friction testing setup (left) along with resulting abrasion created on the bedrock surface (center and right image). Several different loads were investigated with multiple repeats performed where the tire, with the tire in the braked condition, was translated in both the longitudinal and lateral directions to determine the static (peak coefficient of friction, COF, before movement) and sliding (COF when moving) friction using the standard equation (Equation 9).

$$F = \mu N \quad 9$$

Here and in general, test repeats are used to provide a statistically relevant value and assess the range of variability of the result.



Figure 22. NASA GRC Mars Spring Tire prototype in friction testing setup (left) along with resulting abrasion created on the bedrock surface (center and right image).

*Rolling resistance test.* Rolling resistance is a measure of the force opposing motion of the tire on a surface as the tire rolls (sometimes called rolling friction). Tire pressure, tire diameter, tire width, ground conditions, load, internal friction, and tire flexing are examples of parameters that affect rolling resistance. Rolling resistance is, unfortunately, very difficult to measure, since it typically accounts for around 1% to 3% of the tire load (on a highway-type surface)—therefore very accurate measurements need to be made. There are multiple industry standards that exist to evaluate the rolling resistance of typical pneumatic road tires with faster speeds and heavier loads than a typical planetary roving vehicle: SAEJ1269 [26], SAEJ2452 [27], ISO 28580 [28], and ISO 18164 [29]. One way of performing this test is with the tire compressed against a drum surfaced with sandpaper. To isolate the rolling resistance of the tire it is important to take steps to be able to filter out the contributions of the drive train and the terrain itself. This can be done by performing the test on a hard surface with a known/characterized drive system. These standards need to be adjusted to account for the slower speeds, lighter loads, different construct of rover tires, as well as temperature and terrain differences. Best practice requires repeat testing for statistical purposes. The rolling resistance is expressed via the standard equation (Equation 10):

$$F_r = C_{rr}N \quad (10)$$

Here,  $F_r$  is the rolling resistance force,  $C_{rr}$  is the dimensionless coefficient of rolling resistance (CRF) or the force required to push or tow a wheeled vehicle per unit force of weight, and  $N$  is the force perpendicular to the surface on which the wheel is rolling.

*Stiffness characterization.* In addition to these friction related tests, stiffness characterization of the tire can validate analytical models and allow for accurate predictions of its behavior in the overall mobility system. The translational areas of interest include radial, lateral, and longitudinal. To simulate the potential impacts of obstacles, it is recommended that radial stiffness be tested against both a flat plate and a wedge (obstacle) over the full load range. Example of a plate and wedge test are shown in Figure 23, below.

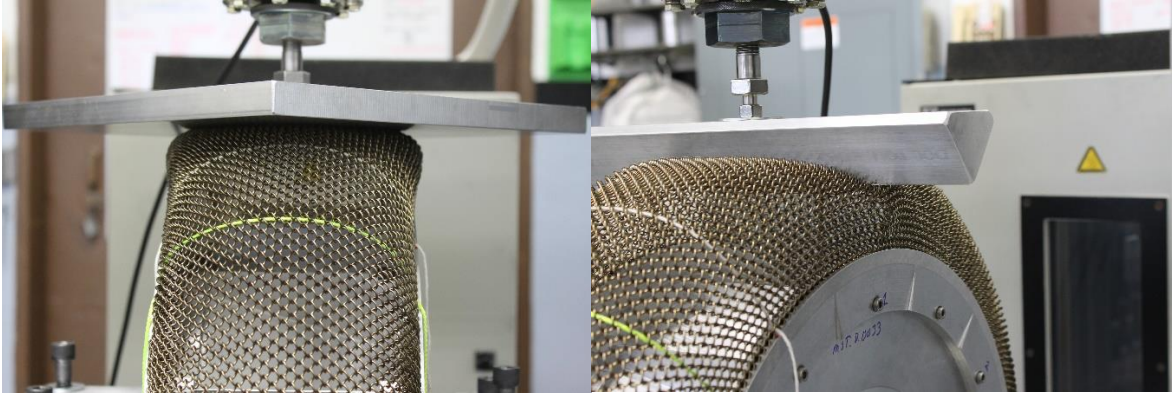


Figure 23. NASA GRC Mars Spring Tire prototype undergoing plate and wedge stiffness testing in a standard electromechanical load frame.

*Vibration testing.* Finally, vibration testing (modal survey, random vibration, and/or sine vibration) is important for a couple reasons. First, it allows for verification that the tire can withstand launch loads and screens for workmanship/design defects in both high—up to 2000 Hz (random), and low—up to 100 Hz (sine), frequency ranges. Secondly, it allows for characterization of the wheel's frequency response so the wheel can be accurately modeled for things like coupled loads analysis (CLA) with the launch vehicle (in accordance with NASA-STD-5002A). Additionally, acoustic testing is used to evaluate the high frequency—up to 10,000 Hz, acoustic pressure environment (typically more applicable at a higher assembly level thus not discussed here). Also, sine burst testing can be used to impart a quasi-static G loading as a strength test (but as it is less about characterization and more about strength it is not discussed further here). Particularly for tires that incorporate unique materials or that are compliant/nonlinear or that have normal modes below 50-70 Hz, vibration testing can be a crucial early characterization test of the tire.

An example of a unique material could be one that is not in the Metallic Materials Properties Development and Standardization [MMPDS] Handbook [30] or otherwise not completely characterized in the relevant environment. Note that the 50-70 Hz threshold is a fairly standard value to likely avoid having overlapping resonances with the launch, but this threshold can vary depending on the project/launch vehicle and does not preclude either the use of tires below the threshold (whose response below said threshold can be accurately modeled) nor a higher threshold. It is typical to do low level sine sweeps before and after vibration tests to verify no response changes/shifts that would indicate damage to the test article. Typically shifts greater than 5% are considered concerning and should be evaluated. Displacement can be measured during testing, for instance via the accelerometers or by using photogrammetry. The displacement data can be useful to ensure adherence to any keep-in or keep-out zones during launch and entry, descent, and landing (EDL). Load cells can be incorporated into the test set up too. This allows recovery of interface forces for use in model correlation and/or force limiting.



If no tailored random vibration spec is provided or available (e.g., coupled loads analysis with the launch vehicle is still pending) a standard generalized random vibration environment is provided in GSFC-STD-7000a, Table 2.4-3 and repeated below:

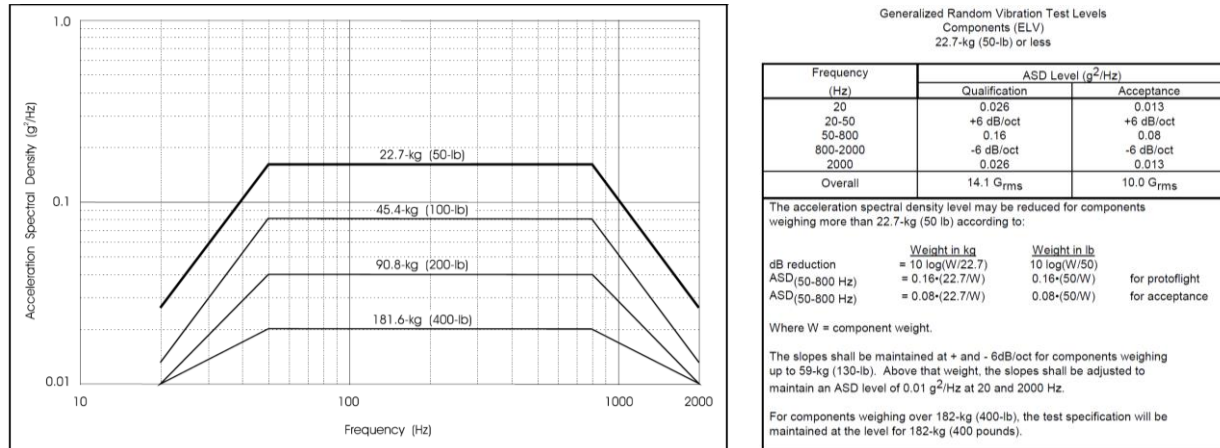


Figure 24. Generalized Random Vibration Test Levels, Components 22.7-kg or less, GSFC-STD-7000A [19].

Note that pretest analysis and sufficient test instrumentation and monitoring should be used. This should allow confidence that the tire both can withstand the applied spectrum and that it is not exposed to unrealistic (resonant) loads that could damage it. In regard to the later, either response or force limiting can be used to notch the input spec as appropriate to compensate for the infinite impedance of the shaker table artificially driving up the base reaction forces at the resonant response(s) of the tire. GEVS contains more details on modal surveys, generalized random vibration test levels, and sine sweep vibration. NASA-HDBK-7004C has in-depth details on the rationale behind, required hardware to, and methods of setting the force-limits for a force limited test. NASA-STD-5002A deals with load analyses of spacecraft and payloads and includes details on establishing forcing functions and mathematical models and for performing analyses and verification of models by tests.

Taken together these characterization tests can provide highly useful information necessary to model and predict the tire behavior.

#### 4.3.3 Identified risk and gaps in knowledge

For more detail on each gap please refer back to Table 2 in Section 2.2.

##### 1. Lack of test standards for planetary rovers and tires

A major lesson learned, discussed in more detail in Table 1 in 2.1, in doing characterization tests is that:

1. *Because compliant tire vibration response can be difficult to simulate, relevant vibration testing should be conducted early in order to correlate the system-level models.*

## 5 GENERAL BEST PRACTICES AND LESSONS LEARNED FROM NASA FLIGHT PROGRAMS

### 5.1 VIPER Rover Program

VIPER (Volatiles Investigating Polar Exploration Rover) is a lunar unmanned rover tasked with prospecting primarily for water ice at the lunar south pole region [31] [15]. The rover is approximately the size of a golf cart and weighs ~430kg (see Figure 25). The rover operates on battery power alone and is able to recharge them with its three side-mounted solar panels. VIPER is designed to operate in the most extreme lunar environments including Permanently Shadowed Regions (PSRs), areas at the lunar poles that have never received direct sunlight and where water ice is expected to exist nearest to the surface.



Figure 25: VIPER Rover Flight Build

#### 5.1.1 Roving Weight Representative Testing

Testing the mobility system at mission roving weight ( $1/6^{\text{th}}$  of earth weight) would likely follow one of the following options: 1) gravity offloading a flight/engineering unit (ex. Active Response Gravity Offload System or ARGOS at NASA/JSC, shown in Figure 26), or 2) building a separate engineering unit that approximately scales gravity. Between VIPER and an earlier rover developed at JSC, Research Prospector, both methods have been utilized.

There are a few considerations to be made when deciding how to approach rover weight representative testing. If using a gravity offloading system, attention should be paid early in the design to allow for ground support equipment (GSE) to attach to the rover for this purpose. The

rover lift points need to be carefully placed to allow for control near the center of gravity. As it is likely that lift points will be needed for the rover regardless of the use of a gravity offloading systems, it is beneficial to plan for these early in the design. The advantage of such a system is that design teams can focus on a single full scale flight design. Engineering units and the final flight vehicle can be tested in a similar manner. The downsides of testing in this manner are that you are limited by the gravity offload systems used. Any simulant or landscapes must be brought in, extra personnel will be needed for testing, and as a result it is likely total testing time will be reduced. Below shows an example of the Research Prospector Rover (a direct predecessor to VIPER) being testing in ARGOS at JSC. The lift points closely match the vehicle's center of gravity.



Figure 26: Resource Prospection Rover in ARGOS

VIPER chose to build a series of engineering units termed the Moon Gravity Representative Units (or MGRU) that approximated the lunar weight of the rover (see Figure 27, Figure 28, and Figure 29). Each unit is progressively more flight like; the first MGRU1 being a simple skid steer rover primarily to test the drivetrain and wheel and the final unit MGRU4 being built from identical parts to the flight unit where possible.



Figure 27: MGRU1 testing at the GRC SLOPE Lab (left) and MGRU2 driving at the JSC Rock Yard (right)

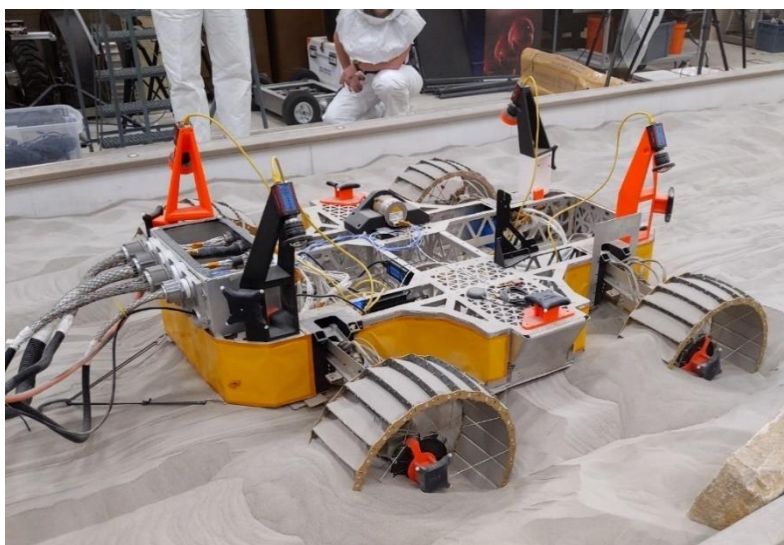


Figure 28: MGRU3 mobility testing at the GRC SLOPE Lab



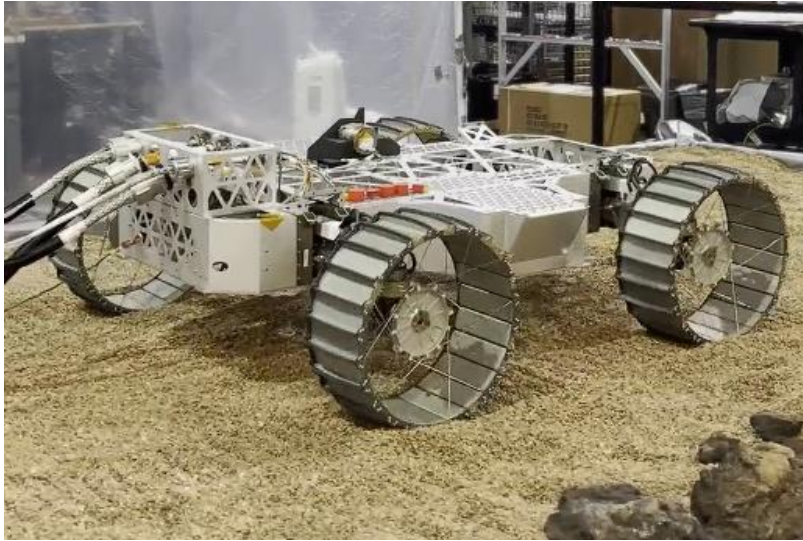


Figure 29: MGRU4 being tested at NASA Johnson Space Center

The engineering units typically were slightly heavier than the ideal weight, but still performed well. Subsystems such as avionics, power, motor controllers were offloaded and tethered to better match the weight on wheels. The end-product consisted of full-scale mobility corners (suspension, steering, & drivetrain) mounted on a minimalist sheet metal chassis. Configurations were added to include telemetry and the correct center of gravity, but those configurations were even heavier than the base configuration. Though the weight on wheels during laboratory testing was slightly higher than expected during the mission, this was accepted as a conservative case, as it was believed that the tractive performance of the rigid wheels would be better with lower loads.

#### *5.1.2 Wheel Endurance Testing*

Rover wheels design can be difficult to verify analytically due to a number of factors. While load cases can be bounded, the number of possible loading combinations is infinite and frequency of each case largely unknown. Therefore, margin (in terms of distance or terrain features) is typically added when conducting single wheel endurance testing. For VIPER this was accomplished by driving 2 X the required travel distance (see Figure 30).

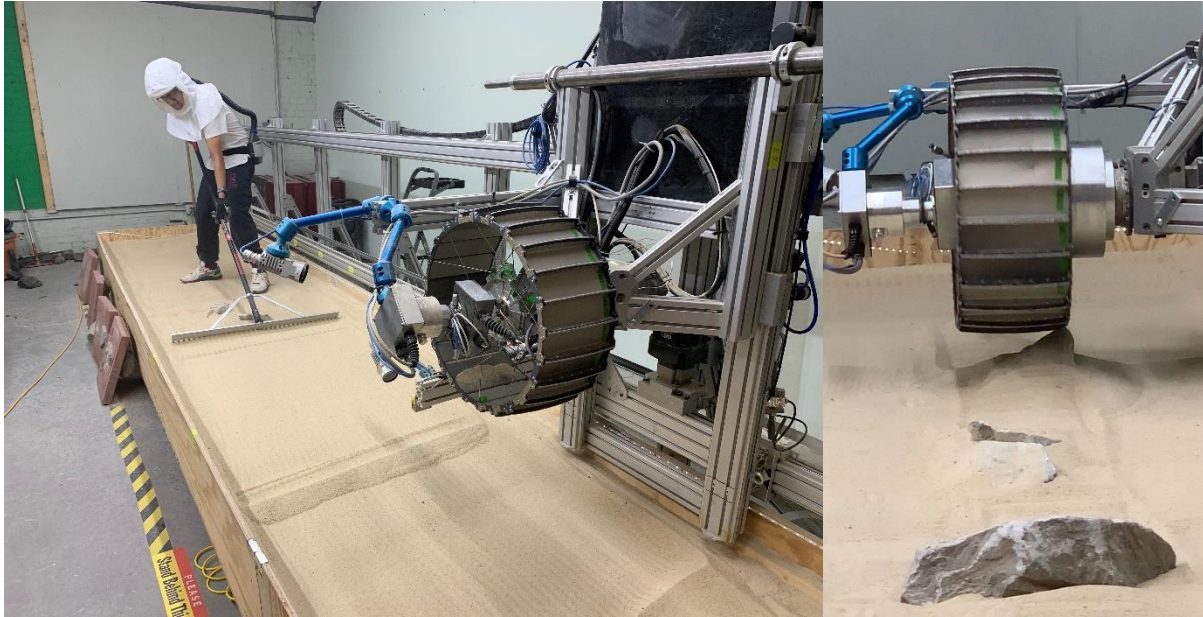


Figure 30: VIPER Wheel Testing at ProtoInnovations Test Track

The endurance test was run on a 6 m linear track (4 m usable) with a wheel run back-and-forth for the distance of 2X lifetime travel (2X 20 km). During the testing both the slope, rock distributions, and downforce were varied to provide a complete test environment similar to the mission traverse for a total of 28 different setups. Analogous slopes were created utilizing force control along the axis of travel of the wheel. The slopes and rock distributions were determined using the environmental specification while assuming no obstacle avoidance by the driver in a 40 km Monte Carlo simulation. The downforce of the test was determined by using static analysis of expected rock-climbing scenarios from the Monte Carlo simulation and verified with measured rock-climbing data from the MGRU test vehicles.

One of the limitations of the testing was that downforce was set as a constant for each run by stacking weights onto the wheel, when in fact the downforce varies significantly per wheel during a rock climb event. In these cases, we erred on the side of conservative testing and set the downforce to the max expected for the run. This meant that in order to obtain a momentary high downforce for a specific rock climb, the wheel would experience a significantly greater downforce during the entirety of the run.

Other limitations include the difficulty simulating the interactions of the four wheels. For instance, the single wheel may get momentarily stuck on a rock climb as it loses tractive force causing significantly more wear to the test wheel as it rotates on the rock with little forward motion. With an actual vehicle, the other three wheels will likely provide the tractive force to climb the rock in a reduced timeframe. Force control along the axis of travel was used to reduce this effect, but it could not be eliminated.

Due to the linear nature of the test setup, we did not experience two load cases: 1) the scraping of the wheel as the suspension arms force the wheels inward and outward, and 2) side loading or torsional loading due to the steering joint at each wheel.

Finally, the test did not include thermal controls. The material properties of the aluminum rim do change slightly at the full mission temperature extremes.

### *5.1.3 Dust Mitigation Testing*

Dust mitigation of mobility actuators represents an important aspect of lunar vehicle design and can be performed coincident with other mobility testing. In brief, dust testing was primarily verified at the level of a mobility corner (one suspension, one steering, and one drivetrain actuator) tested within a sealed environment of lunar simulant kept aloft in the air with circulation. This testing approach is considered by the VIPER team to be harsher than what is expected in the lunar environment.

### *5.1.4 Individual Actuator Testing*

The VIPER rover mobility system contained 3 actuator types: drivetrain, steering, and suspension. Individual actuator testing and actuator motor testing was performed in order to verify performance at the subcomponent level prior to full vehicle testing. Performance testing at the subcomponent level is highly recommended for both flight and engineering units. The test data can prove very useful in the event of a later anomaly with an actuator. Without the early test data to compare against, it can be difficult or impossible to tell when an issue arose, and therefore the cause of the anomaly.

### *5.1.5 Mobility Loads Verification*

In order to verify loads into a vehicle a common approach is to utilize a six-axis load cell near the vehicle drivetrains to gather loads close to the interface points. The MGRU test vehicles did not take this approach due to mass and volume constraints, but instead utilized external load cells to verify vehicle loading.

MGRU vehicles 2, 3, and 4 all contained a single axis load cell at the suspension joint which could measure down force of the wheels, but this data was measured at 10Hz, a rate determined to be too slow to measure peak forces and impacts.

A six-axis load cell ‘rock’ was developed, which was composed of a six-axis load cell on which actual rocks or rock-like billets could be attached to represent different rock climb scenarios, rock climbing representing the maximum load cases derived analytically. This approach allowed us to ground the derived load cases to actual vehicle behavior in the most extreme cases.

The downsides to this verification scheme are that only a narrow set of load cases can be verified and that only the loads at climbing wheel can be measured. Furthermore, loads as the wheel descends the rock will not be captured. Through this testing however, we have been able to verify analytically derived peak loading scenarios between the MGRU test vehicles and endurance wheel testing.



## 5.2 Apollo Lunar Roving Program

The Lunar Roving Vehicle (LRV), developed for NASA's Apollo program, marked a major milestone in extraterrestrial mobility. Designed to endure the harsh lunar environment, these vehicles significantly enhanced astronauts' ability to conduct scientific exploration by enabling them to traverse greater distances on the Moon's surface [32]. Three LRVs were deployed during the Apollo 15, 16, and 17 missions, facilitating a combined travel of 80 km over nine traverses. In contrast, astronauts on Apollo 11, 12, and 14 missions covered roughly 6 km across five traverses [33]. The LRV remains the fastest vehicle to operate on an extraterrestrial body, achieving speeds of up to 18 km/h [34]. Its performance and reliability played a key role in the major scientific discoveries of the Apollo program. While all three LRVs performed admirably, minor mechanical and operational challenges arose during use, offering valuable lessons for future high-speed lunar rovers [35]. This section examines these lessons, focusing on qualification testing, redundancy, low-gravity mobility, dust mitigation, and navigational challenges, in the context of future rover technology.

### 5.2.1 LRV Design

The development of the Lunar Roving Vehicle (LRV) posed unique challenges related to performance, extreme environments, weight, size, and an ambitious timeline. While some of these requirements remain relevant for future rover designs, the strict weight, size, and time constraints were specific to the Apollo program and played a crucial role in shaping the final design. The final mobility specifications for LRV are contained in Table 8 [32] [36] [37].

Table 8: LRV Mobility Specifications

| Specification     | Metric      |
|-------------------|-------------|
| Vehicle Mass      | 209 kg      |
| Fully Loaded Mass | 725 kg      |
| Maximum Range     | 92 km       |
| Maximum Speed     | 14 km/h     |
| Traversable Slope | 25 deg      |
| Parking Slope     | 35 deg      |
| Static Stability  | 45 deg      |
| Temperature Range | 100 – 390 K |
| Wheel Diameter    | 81.3 cm     |
| Wheel Width       | 22.9 cm     |
| Wheelbase         | 229 cm      |
| Track Width       | 183 cm      |

The only available space for the rover was a wedge-shaped quadrant in the Lunar Module (LM), measuring approximately 175 x 193 x 102 cm, requiring a folded storage configuration and requirement to be easily deployable for immediate surface operations. The request for rover proposals was issued six weeks after the Apollo 11 landing, leaving only 17 months to design and deliver a flight-ready qualification unit. Despite these significant challenges, Boeing and General Motors successfully delivered three flight-ready LRVs, and eight LRV test units, which supported the Apollo 15, 16, and 17 missions [36].

The LRV featured several innovative subsystems tailored to meet stringent safety, operational, and transit requirements. This section will specifically examine the mobility subsystem, including the wheels, suspension, drivetrain, and steering [36] [17].

**Wheels:** The LRV used an innovative wire mesh design specifically crafted to address the unique challenges of traversing the lunar surface [17]. This design featured a carcass constructed from zinc-coated piano wire, woven into a mesh pattern, with a spun aluminum hub and titanium bump stops to support high-impact loads. The outer circumference of each wheel was equipped with chevron-shaped titanium treads, covering about 50 percent of the wheel's soil-contacting surface. This tread configuration was determined through tests with lunar soil simulants, which showed that 50 percent coverage provided an optimal balance between flotation and traction.

**Suspension:** The LRV's suspension system had a pair of parallel triangular arms attached to each wheel, similar to a terrestrial dune buggy. These suspension arms transmitted forces through torsion bars, a lightweight alternative to a more typical coil over damper design. In the rover's stowed configuration, the suspension system was designed to rotate approximately 135 degrees, enabling the rover to fold into a compact form that could fit within the Lunar Module for transport. Once deployed, the suspension provided vertical oscillation attenuation through a damper, mounted between the chassis and upper suspension arms. The system's design allowed for a ground clearance of 35.6 cm when fully loaded and 43.2 cm when unloaded, which enabled the rover to tackle obstacles up to 30 cm high and cross crevasses up to 70 cm wide.

**Drivetrain:** The LRV's had four independent drive systems consisting of an 80:1 harmonic drive reducer, a 36VDC series wound brushed motor, a mechanical brake assembly, a decoupling assembly, and an odometer for navigation feedback. The entire drive assembly was hermetically sealed with 51.7 kPa nitrogen to aid in heat transfer and protect from lunar dust. In the event of a failure, each wheel could be decoupled from the drive system allowing free wheeling on bearings.

**Steering:** The LRV utilized a four-wheel steering system, with both the front and rear wheels being independently steerable in a double Ackermann arrangement. This allowed for a highly responsive and maneuverable vehicle, capable of making sharp turns on the lunar surface. In this system, the inner wheels turned at a tighter angle than the outer wheels, enabling the rover to navigate confined spaces and make precise adjustments. The steering mechanism was designed to be redundant, meaning if one system failed, the rover could still be operated using the remaining functional system. The maximum steering angle for the outer wheels was 22 degrees, while the inner wheels could turn up to 53 degrees, providing minimum turning radius of 3.05 m.

**Chassis:** The chassis was constructed using aluminum tubing and sheeting welded together to form three panels. During transit, these panels were folded up to fit within the LM and served to protect the rover and lander from launch and inflight damage. Once deployed, the panels locked into place and remained rigid for the remainder of the mission. The chassis provided a wheelbase of 2.29 m and track width of 1.83 m.

**Fenders:** The wheel fenders were essential for deflecting lunar dust during driving operations, a necessity underscored during the Apollo 16 mission when one fender broke off early. Without the fender, lunar dust was thrown several meters ahead and above the rover, leading to significant

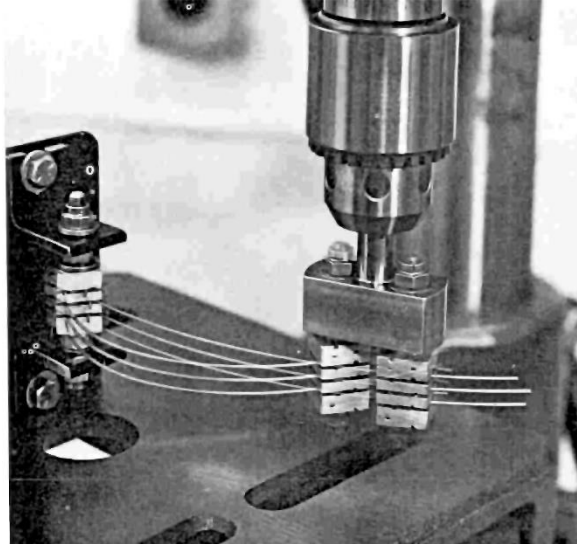
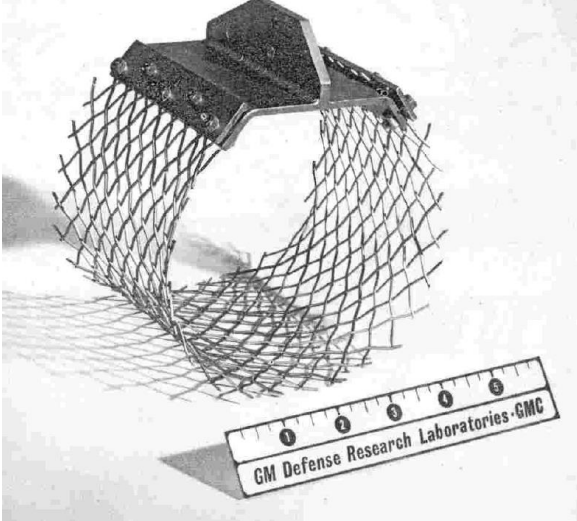
problems such as thermal buildup and obscured visibility of the instrument cluster. The dust was so pervasive that it threatened the seal integrity of the EVA suits and further impaired visibility. A similar fender failure occurred during Apollo 17, but an improvised repair successfully mitigated the issue for the remainder of the mission.

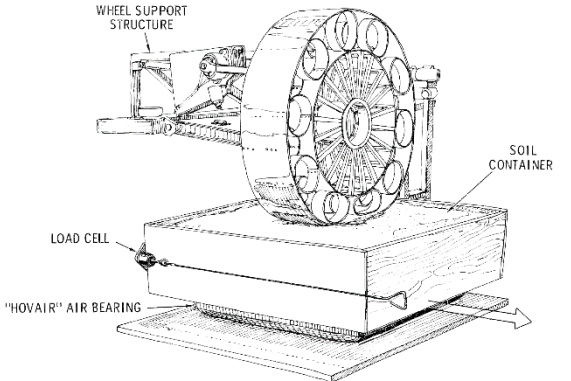
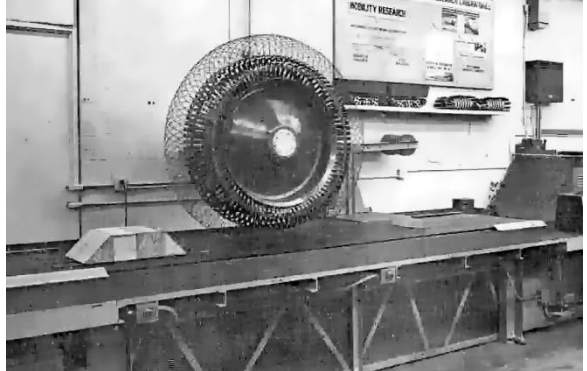
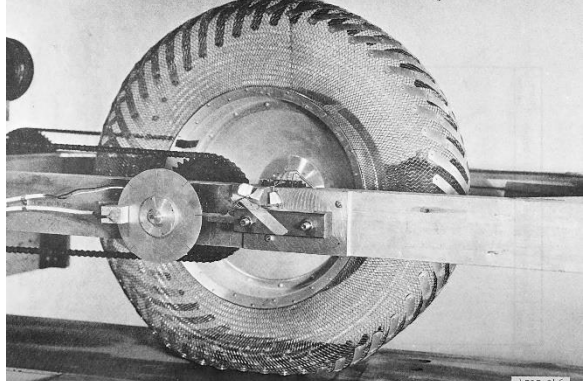
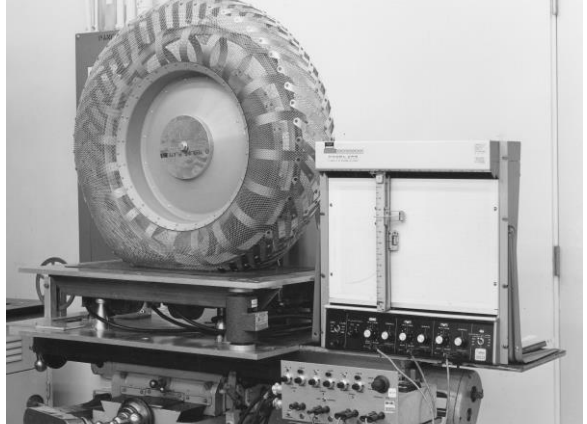
### 5.2.2 *LRV Testing*

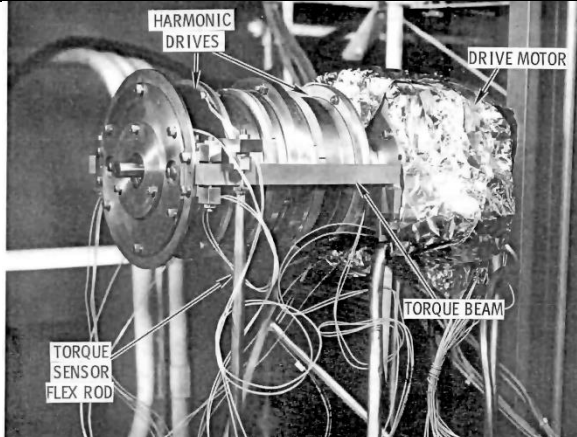
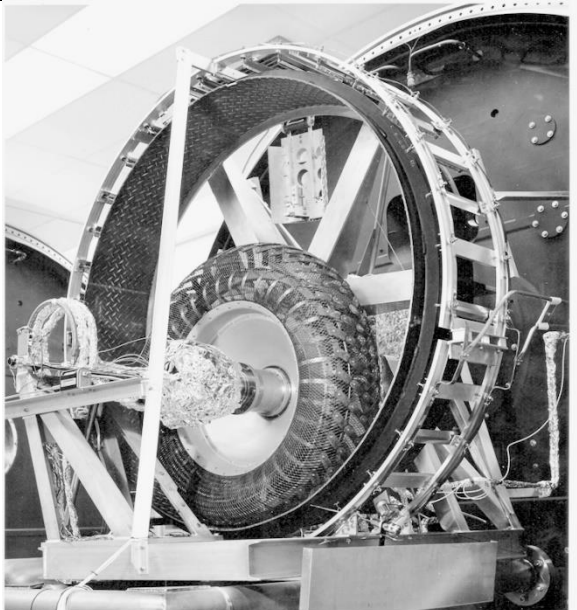
Pre-flight verification and qualification testing were critical to ensuring the Lunar Roving Vehicle (LRV) was rated for human space flight and could withstand the challenges of lunar exploration. A summary of the major tests conducted on the LRV tires and mobility system is provided in Table 9. Design requirements for the LRV flight articles dictated that structural systems must have a safety factor of 1.5 for flight and lunar surface loads, and 1.15 for landing loads [38]. Testing included extensive simulations and assessments in environments designed to replicate launch, landing, and surface loads. These efforts provided essential insights into the vehicle's performance and operational limits. Eight LRV test units were built prior to the first flight rover [36]. The test units were a full-scale mockup, mass model for LM structural assessment, two 1/6<sup>th</sup> weight for storage and deployment tests, a 1-G trainer for astronaut training, a vibration test unit, and a qualification unit for vacuum, temperature, electromagnetic, and full system checkout. During design and testing of the mobility subsystem, significant attention was given to the wire mesh wheel design [32]. Testing focused on durability, traction performance, soil simulant interactions, and functionality under ambient and vacuum conditions. This section will discuss some of the testing performed by NASA, Army Waterways Experiment Station (WES), Boeing, and General Motors (GM) on the wheels and mobility subsystem with corresponding references for detailed information.

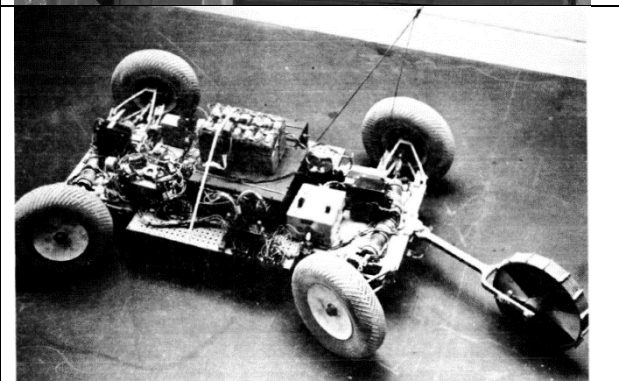
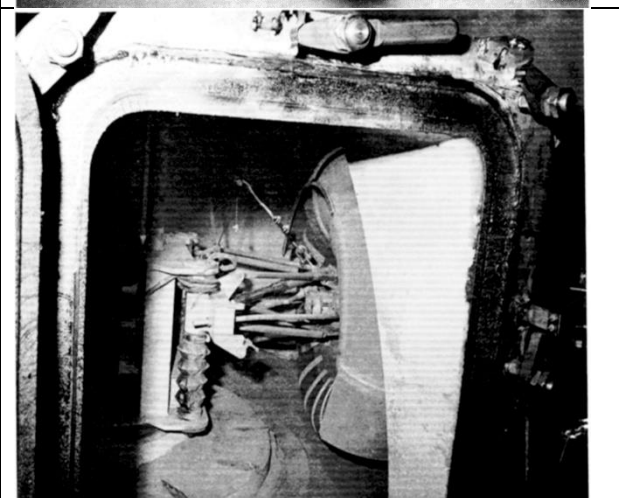
**Soft Soil Performance:** Several wheel design and configurations were tested at WES [39] and GM [37] to determine the traction performance of the LRV wheel. The primary goals of these tests were to determine the drawbar pull coefficient vs. slip curve, sinkage, effective rolling radius, and motion resistance under various soil conditions, normal loads, and chevron configurations. Testing at WES used a crushed basalt simulant with similar grain size as Apollo 11 and 12 samples. Testing at GM used a dry silica sand.

Table 9: Overview of LRV Tire and Mobility Test Campaign

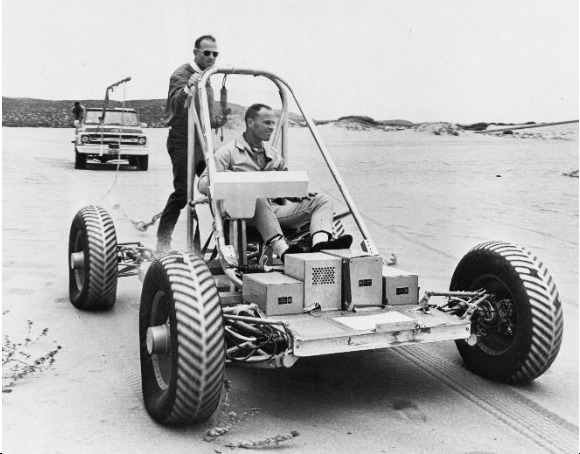
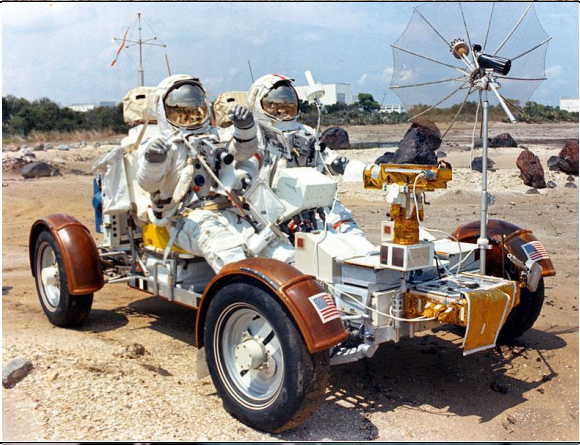
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| <p><b>Name:</b> Wheel Material Screening Tests (Fatigue Test) [40]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> The objective was to determine safe operating stress levels for different wire materials using a tensile testing machine. The depicted test is for assessing fatigue life. It used a rotating drill to cycle wires in bending. The image shows the starting and ending states superimposed.</p>                                         |    |
| <p><b>Name:</b> Wheel Material Vacuum Welding Test [40]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> The objective of this test was to determine if the wire mesh structure would vacuum weld in the lunar environment. The secondary objective was to determine fatigue characteristics of the wires. The samples were placed in a <math>10^{-9}</math> torr vacuum chamber and cycled with a constant deflection at surface temperatures of 422K.</p> |   |
| <p><b>Name:</b> Soft Soil Testing [37]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> GM Terex Division Hudson, OH.<br/> <b>Description:</b> Wheel tests were done to determine the Drawbar-Pull vs Slip, Sinkage, Motion resistance, and Effective rolling radius of various designs for the LRV.<br/> <b>Simulant:</b> Crushed Silica Sand</p>                                                                                                                                                     |  |

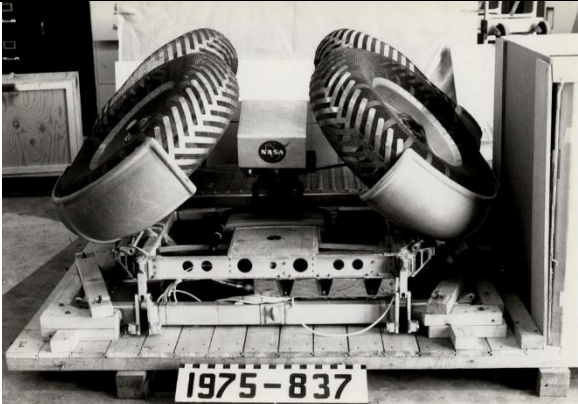
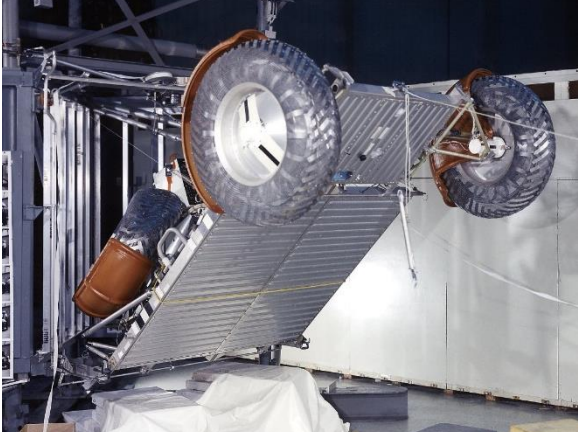
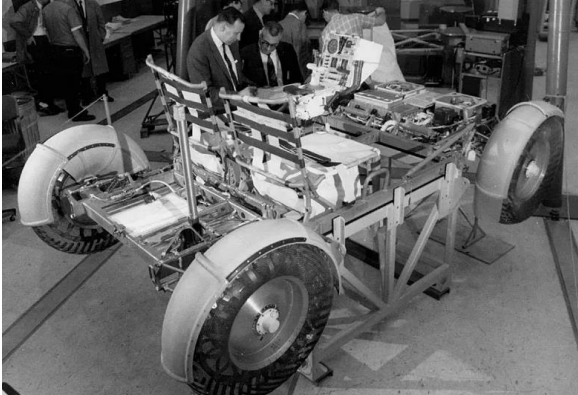
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| <p><b>Name:</b> Steering Resistance Test [40]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> A soil bin was placed on an air-bearing surface with and mounted to a 2-axis loadcell. Different wheels were steered, and the resultant forces were measured.<br/> <b>Simulant:</b> Silica Sand and Perlite</p>     |    |
| <p><b>Name:</b> Rolling Road Test Facility [37]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> The purpose of this test was to understand dynamic loads generated when encountering obstacles and to find endurance limits of the wheels over a smooth surface, single obstacle, and random obstacle course.</p> |    |
| <p><b>Name:</b> Single Wheel Dynamometer [39]<br/> <b>Who:</b> WES<br/> <b>Where:</b> Vicksburg, MS<br/> <b>Description:</b> The purpose of this test was to determine and compare quantitative performance of wheel concepts in various soil conditions.<br/> <b>Simulant:</b> Crushed Basalt (LSS1-4)</p>                                             |   |
| <p><b>Name:</b> Load-Deflection [37]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> Three axis load deflection test for determining stiffness and contact patch for various vertical loads. Normal, Axial, and Tangential loads were measured.</p>                                                               |  |

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| <p><b>Name:</b> Wheel Drive Breadboard Tests [40]<br/> <b>Who:</b> GM/DRL<br/> <b>Where:</b> Santa Barbara, CA<br/> <b>Description:</b> Speed and torque measurements of drive system under ambient and thermal-vacuum conditions.</p>                                                                                                                                                                                                                                                                                                                                         |    |
| <p><b>Name:</b> Carousel Life Test [41]<br/> <b>Who:</b> GM /MSFC<br/> <b>Where:</b> GM/DRL<br/> <b>Description:</b> Long duration high fidelity life test. Circular carousel with soil and obstacles. Constant force off-loader to simulate lunar dynamics and inertial forces.<br/> <b>Simulant:</b> Unknown</p> <p>Photo from Ferenc Pavlics 1971</p>                                                                                                                                                                                                                       |   |
| <p><b>Name:</b> Space Simulator [40]<br/> <b>Who:</b> GM-DRL<br/> <b>Where:</b> AC Electronics Milwaukee<br/> <b>Description:</b> The objective of this test was to provide performance data for wheel and drive assemblies in a simulated lunar environment. The wheel was mounted in a rotating drum that was speed controlled and braked to provide driving loads. Both smooth and obstacle surfaces were tested. The wheel was suspended through a spring-loaded swing arm allowing vertical freedom. The test was performed in ambient and thermal-vacuum conditions.</p> |  |

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| <p><b>Name:</b> Thermal-Vacuum Rolling Road</p> <p><b>Who:</b> Boeing / GM-DRL</p> <p><b>Where:</b> Kent, Washington</p> <p><b>Description:</b> A near vertical treadmill platform was used for endurance testing of the wheel and drive system in a thermal vacuum chamber. The system was configured to mimic lunar gravity dynamics, pressure, and temperatures. The road surface could be smooth or with random obstacles.</p>                                                                    |    |
| <p><b>Name:</b> Scale Model Testing [42]</p> <p><b>Who:</b> WES</p> <p><b>Where:</b> WES, Vicksburg, MS</p> <p><b>Description:</b> A one-sixth scale model of the Lunar Roving Vehicle used in the Apollo 15 mission was built and instrumented to conduct model studies of vehicle mobility</p> <p><b>Simulant:</b> Crushed Basalt (LSS1-4)</p>                                                                                                                                                      |   |
| <p><b>Name:</b> LRV Dust Profile 1/6 g test [43]</p> <p><b>Who:</b> MSFC</p> <p><b>Where:</b> University of Alabama</p> <p><b>Description:</b> 1/6 g testing on a C-135 aircraft inside a vacuum chamber for testing dust mitigation and fender design. A wheel, suspension and fender were driven on a 1.57 m diameter track in lunar soil simulant under vacuum. The entire device was flown on parabolic arcs to simulate the 1/6 g environment.</p> <p><b>Simulant:</b> Crushed Basalt (LSS4)</p> |  |



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| <p><b>Name:</b> LRV Test Mule [44]<br/> <b>Who:</b> GM-DRL<br/> <b>Where:</b> Pismo Beach, CA<br/> <b>Description:</b> Low fidelity test vehicle for assessing operational characteristics of the steering, suspension, and drive modes for the LRV.</p> <p>Photo: NASA 70-H-1159 [45]</p>                                                              |    |
| <p><b>Name:</b> Grover [44]<br/> <b>Who:</b> US Geological Survey<br/> <b>Where:</b> Flagstaff, AZ<br/> <b>Description:</b> Low fidelity rover mockup for crew science and logistics training. Developed to roughly mimic LRV operations using readily available parts for astronaut mission operations training.</p> <p>Photo: NASA S70-53284 [45]</p> |   |
| <p><b>Name:</b> 1-G Trainer [44]<br/> <b>Who:</b> GM-DRL<br/> <b>Where:</b> NASA<br/> <b>Description:</b> High fidelity mobility simulator for crew logistics training. Included full mobility system and support systems for mission training and vehicle operations.</p> <p>Photo: NASA S72-48892 [45]</p>                                            |  |
| <p><b>Name:</b> POGO - 1-G Trainer [44]<br/> <b>Who:</b> NASA<br/> <b>Where:</b> Manned Space Center Houston<br/> <b>Description:</b> Mobility testing using 5/6<sup>th</sup> offloading of the 1-g trainer. Simulates bouncing and reduced gravity effects of driving on the lunar surface.</p> <p>Photo: Screen Capture [46]</p>                      |  |

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| <p><b>Name:</b> Vibration Test Unit<br/> <b>Who:</b> Boeing / GM-DRL<br/> <b>Where:</b> MSFC / Grumman<br/> <b>Description:</b> Mass and stiffness accurate vehicle for load and modal testing in the Grumman Lunar Module.</p> <p>Photo: Smithsonian [47]</p>                                                                                         |    |
| <p><b>Name:</b> Deployment Test Unit [48]<br/> <b>Who:</b> Boeing / GM-DRL<br/> <b>Where:</b> MSFC / Kent, Washington (Boeing)<br/> <b>Description:</b> Test unit for deployment from the LM using the Space Support Equipment (SSE). Presented significant challenges nearly resulting in cancelation of the LRV.</p> <p>Photo: MSFC-7021097 [49]</p> |   |
| <p><b>Name:</b> Qualification Test Unit<br/> <b>Who:</b> Boeing / GM-DRL<br/> <b>Where:</b> MSFC / Kent, Washington (Boeing)<br/> <b>Description:</b> Flight system qualification unit for validation of EM interference, control system operations, data systems, navigation systems.</p> <p>Photo: NASA 71-H-111 [45]</p>                            |  |

### 5.2.3 LRV Performance

Overall, the LRV performed excellent and was a significant contributor to the overall success of the Apollo program. Flight recordings and mission reports confirm that the astronauts valued the performance and reliability of the LRV in-situ. Despite outstanding performance, there were common issues and challenges that are relevant for future rover development.

**High-Speed Maneuverability:** All three LRV missions encountered challenges when driving at speeds above 5 km/h. While rocks were easily visible during traverses, the frequent small craters were difficult to discern against the low-contrast lunar landscape. This often led to suspension bottoming events or abrupt maneuvers. The primary issue with high-speed driving stemmed from

the low-gravity environment, which significantly impacted the ability to stop and steer. Post-mission reports likened the experience to driving on icy or snow-covered roads, requiring careful attention to side slippage, and extended stopping distances [32].

It was common for multiple wheels to lose contact with the ground during normal travel. During the “Lunar Grand Prix,” all four wheels were observed leaving the ground due to bouncing and dynamic responses. At speeds below 5 km/h, astronauts had sufficient control over braking, steering, and throttle to navigate around rocks and craters effectively. The double Ackermann steering system, invaluable for low-speed maneuverability, became a challenge at higher speeds, where its increased sensitivity and reduced turning response hindered stability.

Several times, accidental bumps to the control stick caused the rover to lose control temporarily. While these incidents were minor, they highlighted a potential risk—encountering a large hole, lava tube, or significant obstacle could have posed serious danger to the rover and crew. The key takeaway from these experiences was the need to adjust steering sensitivity based on traversal speed, ensuring high maneuverability at low speeds and enhanced stability at higher speeds.

**Dust Mitigation:** Lunar regolith presented a significant challenge for the LRV and Apollo astronauts. The fine, electrostatically charged particles adhered to surfaces, infiltrated mechanical components, and caused issues for both the vehicle and astronaut suits. The wheel fenders played a crucial role in directing dust away from the vehicle, but their fragility became apparent when failures occurred on the Apollo 16 and 17 missions.

Astronauts observed pronounced “rooster tails” during traverses, especially at higher speeds. This not only reduced visibility but also led to excessive dust accumulation on the vehicle, including the instrument panel, seat restraints, astronauts’ suits, and equipment latches. The thermal radiators, critical for cooling the LRV’s electronics, became coated in dust, requiring additional time for cleaning and reducing their efficiency. The constant exposure to abrasive regolith also raised concerns about long-term wear on the astronauts’ suits, particularly at the joints and seals, where dust infiltration could compromise integrity.

The Apollo experience underscored the necessity of improved dust mitigation strategies for future lunar exploration. While temporary solutions, such as makeshift fender repairs using maps and clamps, were implemented, the lessons learned from these missions highlight the need for more robust vehicle shielding, dust-resistant materials, and effective cleaning techniques for sustained lunar surface operations.

#### *5.2.4 Conclusions*

The key requirements for the LRV included lightweight construction, ease of operation in low-gravity conditions, and the ability to navigate varied terrain types, from fine lunar regolith to rocky outcrops. Additionally, the vehicle needed to accommodate two astronauts and carry scientific equipment while ensuring a reliable performance in extreme temperature fluctuations and exposure to lunar dust.

The operational experiences gained from the LRV during Apollo 15, 16, and 17 missions yielded significant lessons in traction and mobility. The vehicle's performance in varying lunar terrain

underscored the importance of wheel design and tread patterns, which were critical for maintaining grip and stability on loose regolith. Additionally, the LRV's ability to overcome obstacles and steep inclines informed future designs for mobility systems in extraterrestrial exploration. The challenges faced, such as wheel slippage and the impacts of lunar dust on performance, have provided invaluable data that continue to influence the development of planetary rovers and vehicles intended for future missions, both on the Moon and beyond.

## **6 CONCLUSION**

The material presented in this paper is a compilation of the best practices and lessons learned by NASA for roving vehicle mobility testing. Where applicable, relevant standards and resources have been recommended, though in many cases, no known standards yet exist. Rover and tire providers should use this information as they see fit. There are also many gaps in test methodology that need to be addressed, especially for large fast-moving roving vehicles, such as LTV. The authors plan to address these gaps and provide an update to this paper in late 2025; however, it is unlikely that all the gaps will be addressed by then.

### **6.1 Future plans**

The authors plan to release a revision to this paper in late 2025 with additional information gained via further literature reviews, internal assessments of test methods, and discussions with experts in related fields. During this time the authors also plan to engage regularly with LTV providers to identify testing priorities. The following sections will also be included in the later revision of the paper:

- Best Practices and Lessons Learned from the Mars Rover Programs
- Best Practices and Lessons Learned from Commercial Vehicle Industries (off-road vehicles, tire providers, agriculture industries, etc.)
- Best Practices and Lessons Learned from Commercial Space Companies
- Best Practices and Lessons Learned from International Space Agencies

The focus will be on addressing the major gaps identified in this paper, as well as ones identified through discussions with the LTV providers. However, it is unlikely that all gaps will be addressed in the next version of the paper and future work may be needed to further develop the necessary methodologies. Eventually many of these best practices may lead to official standards as well.

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