Developing a Motion-Based System for Lunar Vehicle Handling Qualities Testing

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Abstract— **Motion and visual cue influences are critical in any simulator system, as they impact multiple aspects of the human's neurovestibular and visual systems. Cues of real motion proceeds to the brain before cues of visual change. It is important therefore for simulator motion cues to exist and to match those realistically with those of the real vehicle to provide transferable training of the activity for operations. The United Kingdom's Royal Air Force Institute of Aviation Medicine (1989)[1] stated that motion platforms are the only simulation devices capable of fully stimulating the body motion sensors. They confirmed that motion platforms can impart accelerations to the whole body and therefore exercise the automatic motion feedback-loop that operators are used to. With both visual and motion cues handling the vehicle becomes more realistic. Strachan (2019)[1] confirms motion cueing from a well set-up motion platform has been found to be important especially in conditions such as night or reduced visibility where motion cues may be more relied upon. As of this writing, the only lunar rover motion simulator is housed at the General Motors (GM) Milford Proving Ground, which only simulates the motions of a traditional car. A NASA Test Team proposed to complete a motion-based simulation system for NASA's Lunar Terrain Vehicle (LTV) which resides at Johnson Space Center's Systems Engineering Simulator facility. This activity integrated existing fixed base simulation capabilities with a newly procured six-degree of freedom motion base platform for the design, development, evaluation, and training associated with the LTV project. This would incorporate a South Pole Lunar virtual reality simulation using Lunar Reconnaissance Orbiter 5m/pixel high-resolution imagery and Unreal 5.2 Virtual Shadow Maps, combined with a virtual reality (VR) headset, integrated within a rover cockpit on a Mikrolar Motion Platform for evaluating human performance and vehicle handling qualities for concept roving vehicle designs. The motion-based system received its Human Rating Certification on March 2023. To begin testing the new facility, a preliminary handling qualities study was conducted. The objectives were to determine if there is a correlation amongst three handling quality methods of performance for a lunar vehicle and to understand the effects of a simulated 1/6-g loads and visuals with a motion platform on the operator while in a 1-g physical environment. The capability this system provides directly benefits the NASA's Extravehicular Activity and Human Surface Mobility Program and NASA's Flight Operations Directorate in evaluating the driving qualities of vehicle concepts, human performance related to the operating of a lunar surface vehicle, and assessment of suit related driving impacts. It would also**

provide direct operational benefit by providing a first-in-class and unique simulation platform for the lunar astronaut training curriculum. The empirical knowledge of rover and human performance on this scale is paramount as there is currently no other lunar surface simulator with these capabilities. The result of this study ensures a broadly applicable method of testing for shirtsleeve, unpressurized and pressurized suited rover handling qualities.

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1. INTRODUCTION

Motion and visual cue influences are critical in any simulator system, as they impact multiple aspects of the human's neurovestibular and visual systems [2]. Cues of real motion are proceeded by the brain before cues of visual change. It is important therefore for simulator motion cues to exist and to match those realistically with those of the real vehicle to provide transferable training of the activity for operations. In 1989, the United Kingdom's Royal Air Force Institute of Aviation Medicine (RAF-IAM) [1] stated that motion platforms are the only simulation devices capable of fully stimulating the body motion sensors. They confirmed that motion platforms can impart accelerations to the whole body and therefore exercise the automatic motion feedback-loop that operators are used to. With both visual and motion cues handling the vehicle becomes more realistic. Strachan (2019) [1] confirms motion cueing from a well set-up motion platform has been found to be important especially in conditions such as night or reduced visibility where motion cues may be more relied upon.

However, motion cues must be properly synchronized with corresponding changes in simulator visual imagery, so that they correspond to how these cues are sensed in the real world. Cues of real motion need careful setup. In order to complete the motion-based system, the team's proposed technical approach will use the expertise of the National Aeronautics and Space Administration's (NASA) Softwar,e Robotics and Simulations Team to synchronize the virtual reality simulation visual model to the motion table simulator in a "washout" algorithm development process. This process is critical to develop simulator motion algorithms to provide realistic motion cues.

Currently, the only lunar rover motion simulator is housed at the General Motors (GM) Milford Proving Ground, which only simulates the motions of a traditional car. GM's simulator cockpit has pedals for acceleration and braking with a typical GM interior and a Corvette steering wheel. Our team proposed to complete a motion-based simulation system for NASA's Lunar Terrain Vehicle (LTV) which resides at Johnson Space Center's (JSC) Systems Engineering Simulator (SES) facility. This activity integrated existing fixed base simulation capabilities with a newly procured motion base platform for the design, development, evaluation, and training associated with the LTV. This would incorporate a South Pole Lunar virtual reality (VR) simulation, combined with a VR headset, integrated within a rover cockpit on a Mikrolar Motion Platform for evaluating human performance and vehicle handling qualities for concept roving vehicle designs for surface mobility operations.

The NASA motion simulator can exercise the full range of motion of a rover on the lunar surface with a maximum +/- 25-degree pitch, roll, and yaw incorporating a scientifically accurate South Pole lunar terrain and lighting. The capability provides direct benefit to the LTV project for evaluation of the driving qualities of the vehicle concepts, human performance related to the operating of lunar surface vehicle, and assessment of suit related driving impacts. It also provides direct operational benefit by delivering a first-in-class unique simulation platform for the lunar astronaut training curriculum. The empirical knowledge of rover and human performance on this scale is paramount as there is currently no other lunar surface simulator with these capabilities. The results of this study ensured a broadly applicable method of testing for unpressurized as well as pressurized rover designs.

2. ROVER VEHICLE BACKGROUND

The Apollo Lunar Roving Vehicle (LRV) flew on Apollo 15, 16 and 17 lunar missions (Figure 1). During each mission, the vehicle was used on three Extravehicular Activities (EVA) totaling nine lunar traverses and allowing the astronauts to explore four times more lunar terrain than in previous Apollo missions. However, the LRV was a single use vehicle weighing in at 209 kilograms (kg) (460 pounds) [3]. NASA's new unpressurized lunar rover concept builds on the LRV, with some added unique aspects (i.e., Lunar South Pole operations, suit interfaces, science, etc.) that requires a different vehicle configuration called the Lunar Terrain Vehicle (LTV) (Figure 2). The additional expanded functionality the LTV will provide includes being reusable with a service life of approximately 10 years [4]. The vehicle will have the ability to survive eclipse periods and shadow periods. It can be remotely operated from Earth, Gateway or the Human Landing System (HLS) lander to traverse to points of interest and interface with science instruments and payloads such as a manipulator arm. NASA will bring this concept vehicle to life by building the LTV Ground Test Unit (GTU) as an engineering asset for studying flight vehicle design. The GTU will generate and provide reference data for use across the Artemis architecture working groups and studies. This reference data will be backed by engineering analysis and will provide a framework to evaluate proposed design requirements. The vehicle will also provide a reference point when reviewing vendor proposals.

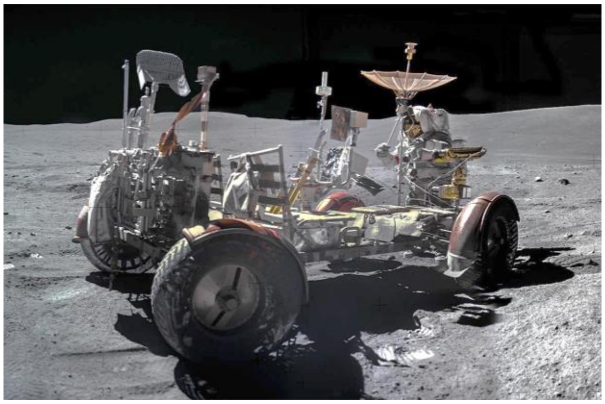


Figure 1. The Apollo Lunar Roving Vehicle (LRV). [Curiosity NASA]

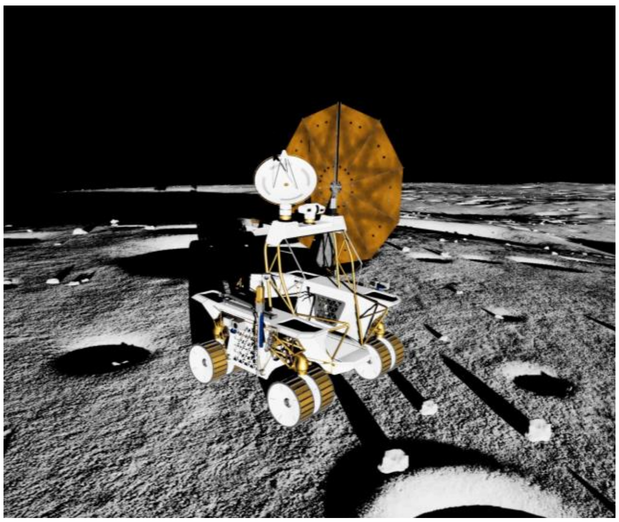


Figure 2. The Lunar Terrain Vehicle (LTV).

3. Motion Table Development

The first lunar rover simulation was a US Air Force SMK23 flight simulator modified and built at Marshall Space Flight Center (MSFC) in the late 1960s (Figure 3). The simulator consisted of a moving map, sensors, a small television camera that viewed the lunar terrain while a subject was in the LRV simulator (Figure 4). This moving base simulator with a crew station was located on a platform that responded to the movement of the simulated vehicle motion as it traveled over the moving lunar map [5]. The map used in the simulator was an orbiter image of the Maria area that was smooth and the type of terrain the LRV was expected to operate in while on the Moon.

Figure 3. A subject using an Apollo type vertical pistol grip controller in an LRV simulator with a large circular TV monitor display [5].

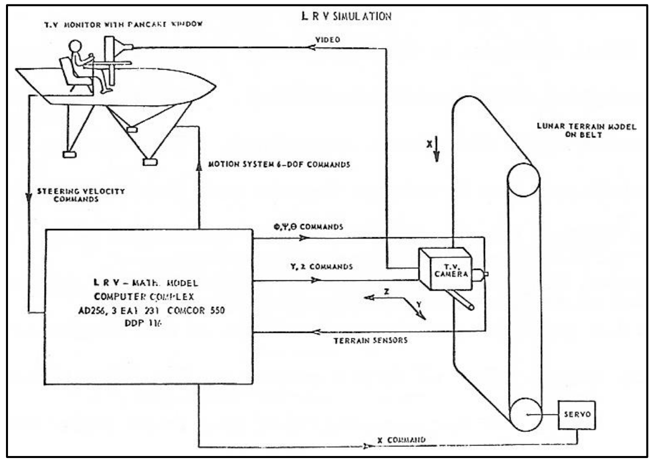


Figure 4. Operational diagram of the LRV simulator [5].

JSC Motion Table Lunar Simulator

Motion based development for lunar driving simulations is a valuable asset for system engineering and training where real environments are not accessible or available. Phase one of the project was to allow a shirt-sleeve test subject to sit on the motion platform and interact with a lunar rover using VR, experiencing the physical results of their interactions. NASA's Center Innovation Fund (CIF) Internal Research and Development (IRAD) project provides NASA agencies and their workforce with hand on opportunities to develop innovative center capabilities in support of NASA's sustainable exploration mission objectives. Due to this funding, in addition to matched funding from NASA's Extravehicular Activity and Human Surface Mobility Program (EHP), the study facilities in this plan were made possible.

The objective of developing the motion platform for NASA is to support the lunar surface mobility development and training for the duration of EHP. The facility integrates common NASA developed simulation assets for lunar South Pole, lighting and navigation, and incorporates a motion simulation capability. Once the facility is developed, it is available to assist potential rover vendors with design and test as requested. It enables human factors engineering studies and will be an option for mission planning exercises and surface mobility training for future Artemis missions.

The Mikrolar Motion Table

The development project started in October 2022. The Systems Engineering Simulator (SES) team had already purchased the Mikolar Motion Table making facility modifications on the Mini Dome (Figure 5) located in Building 16 at Johnson Space Center (JSC). To house the unit which was sitting on a pallet (Figure 6) along with a proposed single race car seat (Figure 7). The device provides a six-degree of freedom motion platform which supported human-in-the-loop (HITL) simulations for lunar surface mobility handling qualities in June 2023. The platform is approximately 2 meters in diameter and approximately 117.167 centimeters (cm) in height with a total height range of 147.32 cm (Figure 8). Table 1 shows the operational specifications of the motion platform. In January 2023, with the motion platform installed in the Mini Dome, Mikolar representatives came over to NASA to commission the motion platform and run reliability testing on the device to ensure proper installation and performance. Several of the SES engineers were trained on the commercial capabilities of the Mikolar system software at this time.

Figure 5. The Mini Dome facility prepare in 2022.

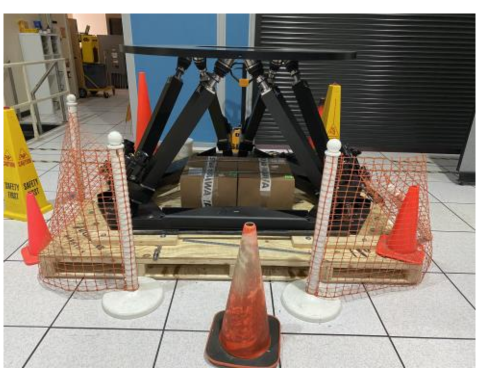


Figure 6. Mikrolar table on a pallet in January 2022.

Figure 7. The race car seat on a frame in January 2022.

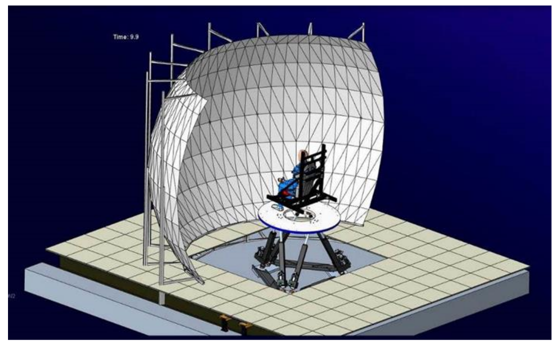


Figure ***8***. The proposed B16 Mini Dome motion-based system.

Table 1. *Mikrolar Motion Table Specifications*

SPECIFICATION	DATA
Payload	2,500 lbs.
Platform	69.25" Ø
Degrees of Freedom	Six
Loading Height	46.25"
Acceleration (X, Y, Z)	0.5 g
Velocity (X, Y, Z)	24"/sec
Range of Motion (X, Y)	±25"
Range of Motion (Z)	±12"
Range of Motion (Roll, Pitch Yaw)	±28°
Repeatability	1 mm
Accuracy	1 mm
Mechanical Brakes	All Axes
Electric Motors	Six

The Visual Lunar Software

In parallel to the motion platform installation and performance testing, NASA's Simulation Team built the visual simulation framework of the lunar South Pole terrain using their custom trick [45] simulation framework. The visual simulation was first used in a HITL in May 2020 with the test team examining the effects of lunar lighting on rover driving and EVA events. The simulation team acquired NASA's LTV front entry rover model as a reference design. It consists of a multi-body dynamic model developed using MulitBody Dynamics (a NASA custom internal software package) (MBdyn) and the Johnson Space Center's Engineering Orbital Dynamics (JEOD) model [46], a representative electrical power system model developed using General-Use Nodal Network Solver (GUNNS) software [47], contact model developed using Pong, and a simple terramechanics model. The multi-body model consists of dynamic model for rover chassis, suspensions, and wheels. It works with the contact model to determine the normal force and tractional force on each wheel. The simulated LTV can traverse forward and backwards, has a turning radius of zero (i.e., can turn in place), crabbing functionality, and can move at speeds up to 12 kilometers per hour (kph) (Figure 9). The LTV simulation capabilities are shown in Table 2. With lessons learned for the 2020 HITL, the simulation team decided to make a major jump for a custom inhouse graphics software development package to the Unreal 5.2 virtual reality software development package. The upgrade did enhance the visual rendering of the vehicle.

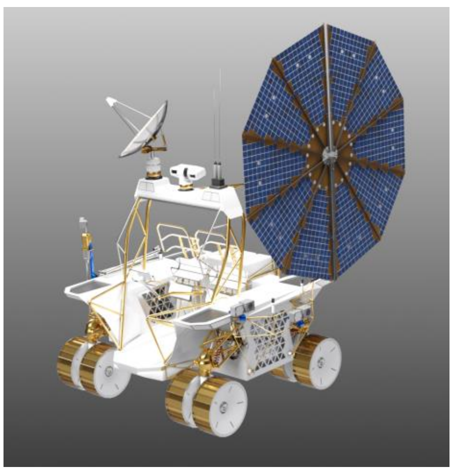


Figure 9. The virtual front entry LTV test vehicle.

Table 2. *LTV Virtual Simulation Capabilities*

Length	2.83174	meters
Width	3.34807	meters
Height	1.94211	meters
Max Crew Capacity	2	Crew
Max Payload Mass (nominal)	800	Kilograms (kg)
Max Speed (level terrain)	15	Kilometers per hour (kph)
Min Slope Climb (uphill@800kg payload)	20	Degrees (deg)
Contact Model	Frame geometry and Pong contact with 4 wheels models	
Steering Modes	Ackerman Crab Mode	Like standard vehicle Wheels can strife at different angles
Gimbal Rate Max	2.0	Radians/second (rad/s)
Wheel and Soil Interaction	Terramechanics Model	Custom built off LRV model
Note: *LTV virtual model is based on NASA LTV reference design.*		

The rover’s terra-mechanics model for wheel to soil (regolith) interaction resembles the lunar surface more closely. Early modeling used regolith parameter values from studying the sample collection from the Apollo missions [6,7,8,9]. The terramechanics model calculates compression resistance and bulldozing resistance on each wheel based on the wheel-soil interaction. It also contains a simple rolling resistance to account for non-soil frictional resistance. These models are integrated together to simulate the driving dynamics and power consumption of the rover during traverse. Today’s model assumes uniformity of lunar soil properties across the lunar surface and is used to calculate the overall soil resistance on the wheel due to compression and bulldozing.

The biggest improvement in the visual simulation was seen with the lunar South Pole integrated lunar terrain, crater clusters, and rock contact models. The lunar terrain incorporated into the simulation is a high-fidelity representation of the 16 November 2024 lunar day with the South Pole lunar sun elevation of 1.2º and a notional 500-m radius landing area and a notional 500-m radius habitat area (Figure 10) approximately 17 kilometers (km) from the lunar south pole, as well as a 500-m radius area inside the Bear Paw (Figure 11) approximately 8.9 km west from the landing site. Terrain data is based on 5m/pixel Digital Environmental Model (DEM) data and 1m/pixel high-resolution imagery from the Lunar Reconnaissance Orbiter (LRO). This terrain was then augmented with sub-resolution features, such as rocks and craters, based on statistical models collected from the LRO imagery. Most of these features were placed using randomization scripts, which aligned with the statistical models generated from LRO imagery; however, a small subset of craters was carefully placed to align with real crater sizes and positions. This data was provided by the JSC Astromaterials Research and Exploration Science Division (XI) scientists and was collected from the LRO imagery. A 500-m wide corridor between the landing site and Bear paw area was populated to the same level of fidelity using the same techniques. Using these images, comparisons can be made on the accuracy of the size and distribution of the sub-resolution features added to the simulated environments. This traverse path was used for the longer driving duration portion of the study.

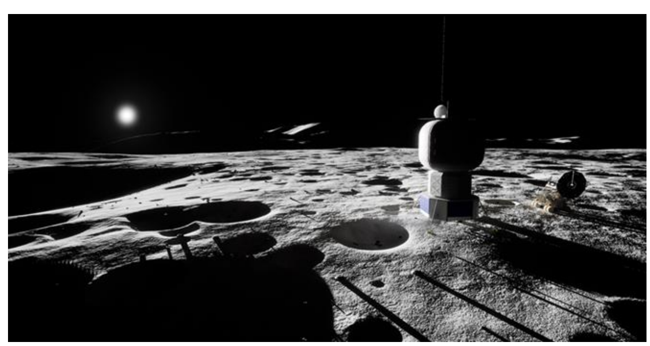


Figure 10. Screen capture of Artemis Base Camp terrain.

Figure 11. Screen capture of Bear Paw terrain.

The simulated lighting is modeled using the virtual reality engine Unreal 5.2. The current lighting model is based on a model called Virtual Shadow Maps (VSM) with a resolution of 16k x 16k (k-thousands) pixels (Figure 12). VSM delivers consistent, high-resolution motion picture quality shadowing using Nanite Virtualized Geometry, Lumen Global Illumination and Reflections and World Partition features. These models allow for the approximation of multipath (or bounce) lighting while maintaining real time performance. Eye adaptation to the light is not currently simulated in our test simulations; however, the SES simulation team is working on an implementation method.

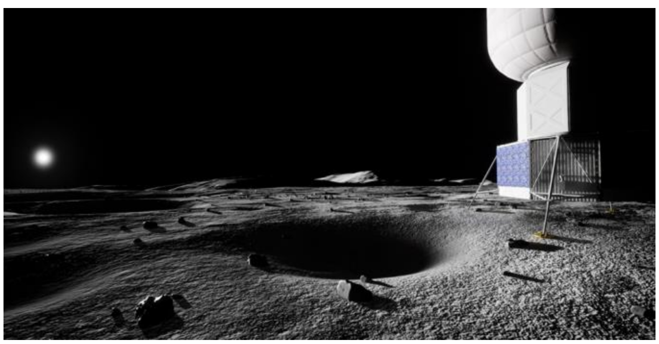


Figure 12. The simulated South Pole Lunar environment.

Motion Table Architecture

With the visual simulation and initial motion platform calculations complete, the team installed the single seat cockpit onto the platform and started the initial washout process syncing the visual simulation with the physical motion of the table. This was started in late January early February 2023. The team had developed a full motion platform architecture (Figure 13) including a VR Simulation Host Computer including a VIVE Pro 2 headset with 1440 x 1600 pixels per eye resolution with a 90 Hertz (Hz) refresh rate and a 110-degree field-of-view that syncs simulation command data with Systems Engineering Simulators Motion Table (SESMT) console computer. The SESMT Operator Console System which controls the table motion, simulation host computer also receives user input commands. Next architectural element in the system is the SESMT Electrical Cabinet housing the ACS SPiiPlusES motion controller and the Yaskawa ∑-7 SERVOPACKS. The Independent Safety System which monitors the position and orientation of the subjects head using HTC VIVE 3.0 Trackers with a VIVE 2.0 Base Station with a 10m x 120m coverage. The safety system also includes three executable emergency stops (E-stops) when safety limits on the table are exceeded. There is a High-Definition Audio/Visual (A/V) System with two to three 1080p high-definition video cameras, two to three video displays with A/V operator having the capability of audio/video recording and live-streaming. There is also a dual-channel wireless communication intercom system for the entire team and test driver. Finally, the Single Seat Mockup Rover Cockpit with an adjustable seat and 5-point harness, a generation 3 Small Pressurized Rover (SPR) joystick hand controller, safety railing and a slip resistant deck. An adjustable footrest was added right before the IRAD testing began.

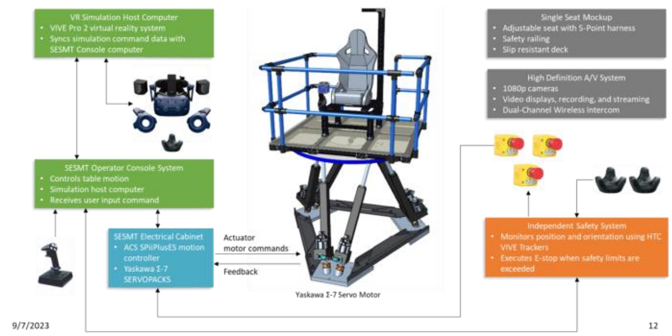


Figure 13. The SES Motion Table (SESMT) Architecture.

Motion Table Human Certification

The team received their human rating certification on 31 March 2023. Over the next two months, the motion table teams refined some hardware for stress analysis, started another washout process of the visual simulation and physical motion of the table using internal team members as human subjects to calculate the table. Study tasks and traverses had to be planned and tested as well as running some dry run test of the test protocol. Finally on 7 June 2023 the first HITL testing of the motion table began. The test team ran thirteen subjects for an LTV handling qualities study and finished testing on 28 June 2023. Seven months from the time the team started developing the motion table system to successful testing (Figure 14).

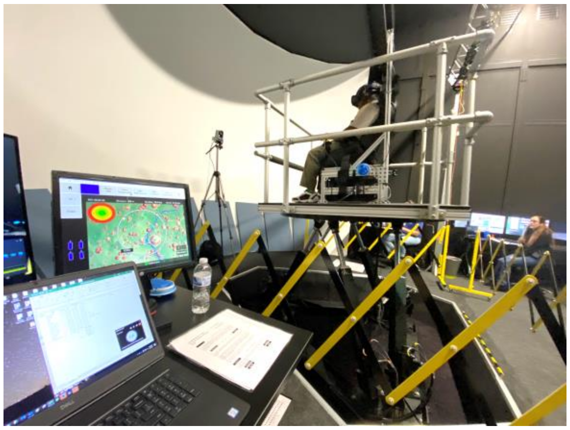


Figure 14. The finished Mikrolar motion table system.

Figure 15. The CH Product MV4 Joystick in the SPR Generation 1B cockpit during field testing in 2009.

4. HANDLING QUALITIES STUDY

There were two objectives for this study that the team investigated to advance the general knowledge of using a motion platform:

- To determine if there is a correlation amongst the methods, or a combination thereof, for scoring handling qualities of a lunar vehicle.
- To understand the effects of a simulated 1/6-g loads and visuals with a motion platform on the operator while in a 1-g physical environment

The outcome products of the study included handling quality data based upon three standard handling quality scoring methods to assess potential correlations amongst the scales to help in determining the most appropriate scale for future efforts. This feedback will provide information to guide future revisions of NASA EHP-10021 LTV System Requirements Document (SRD). Finally, in order to acquire a more comprehensive understanding of the effects on a subject the Kennedy Simulator Sickness Questionnaire (SSQ) was also used while driving a lunar rover using 1/6-g loads and visuals while in a 1-g physical environment for improving future evaluations and training.

Study Hand Controller Hardware

A capability which was not a part of the Ackermann steering functionality of Apollo was crabbing, where a vehicle can strafe across the surface at a chosen angle. During the SPR concept development phases from 2007 to 2022, NASA chose to use the CH Products 3-axis joystick which includes four buttons, one center top hat switch and two light emitting diodes (LEDs) (Figure 15). Rationale for this type of joystick was with the extra degree of freedom in the yaw direction gave engineers a way to incorporate the crabbing function without relying on display software.

Study Design

Testing utilized thirteen engineering test drivers of various backgrounds, in a shirtsleeve environment using a single-set LTV cockpit on a motion table in the SES mini dome facility (Figure 16). The test driver population accomplished a task then rate that task using all three handling qualities scales. Handling quality scales were randomized for each task, each overarching scenario and each subject. Testing used two test courses: 1) a Test Track consisting of seven individual driving tasks and 2) a Long Traverse course that gave the test driver some experience in what a nominal lunar South Pole rover mission would be like driving from a Lander site to a habitat site.

Figure 16. The motion table in the SES Mini Dome facility.

Before any testing begins, the test conductor asked the test driver to answer the Kennedy Motion Sickness Scale (SSQ) questionnaire to get a response on how they are feeling. The SSQ was administered approximately 15 minutes into testing, after each scenario, and again at the end of testing. If at any time the test driver felt "off" then testing would be halted, and time given to the test driver to recover.

A familiarization session of approximately 15 minutes was given to the test driver to acquaint themselves with the controllers and the reactions of the motion platform around a potential Artemis Base Camp (ABC) site. With the familiarization session complete, the test conductor placed the test driver at the starting point for the first test track driving task. After task completion, the test driver would be asked to rate the handling qualities of the controller for that task and provide any comments. Then the test drive was teleported to the next task site. This continued until all seven individual test track tasks were completed. These short test track tasks were designed to test different aspects of the rover handling qualities, such as crabbing, constant turns for inspections, avoiding craters in a crater field, straight line driving/braking, slopes (up, down, cross), under different terrain conditions while in a 1/6-g environment (Figure 17). Track parameters were taken for the automotive community, the military vehicle testing standards and the aerospace community [10,11,12,13,14,15,16]. These test track tasks took approximately 45 minutes to complete. This tested the responsiveness and maneuverability of the vehicle along with the test driver's ability to drive the vehicle using the controller(s) driving capabilities.

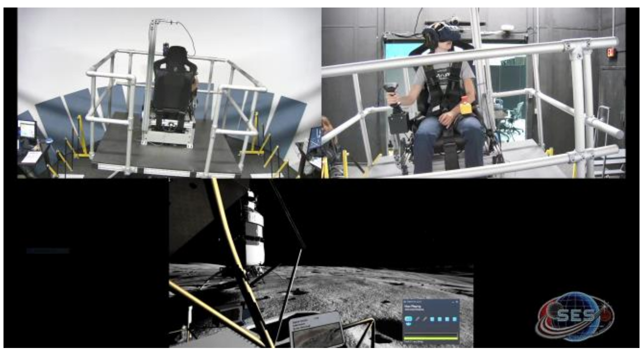


Figure 17. Test driver on the motion table.

After a 10-minute break, the test driver would be reseated on the test apparatus and made as comfortable as possible. The test conductor placed the test driver at the ABC site. The test driver was told their objective was to traverse the 5 km distance (Figure 18) from the habitat site to the Lander. This long traverse was designed by XI as a power efficient traverse, meaning the vehicle's solar panel was always in the sun. Test drivers experienced a variety of terrain features along this path which would be seen on a nominal lunar traverse (e.g., rocks, craters, sun directions, slopes, etc.). The traverse took approximately 45 minutes to 1 hour to complete (Figure 19). The long traverse tested the test driver's ability (the skill required of the operator to do the action) to drive the vehicle using the controller(s) driving capabilities while avoiding terrain features, which assisted in the evaluation of the controller handling quality responsiveness to the test driver's inputs. After the completion of the long traverse, test drivers gave a handling quality score and completed a post-test acceptability questionnaire on the controller.

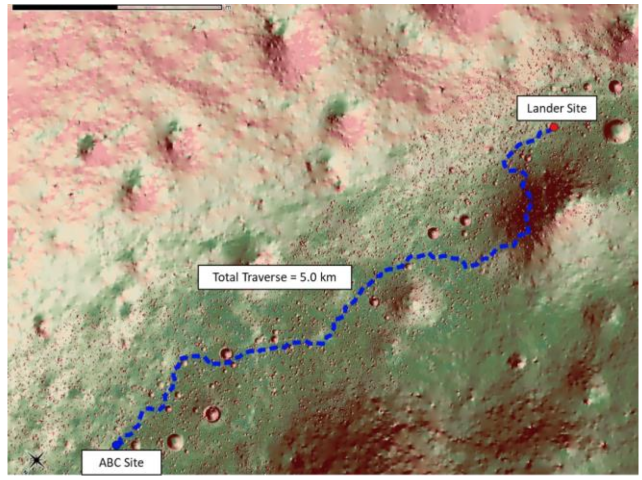


Figure 18. The 5km long traverse course.

Figure 19. Test driver on the motion table during the long traverse course.

Study Methodology and Data Collection

Objective data collected from the simulation were .csv files collected by the simulation team and given to the test team for analysis. Table 3 is the objective data which was required.

Table 3. *The Study's Objective Data*

Data	Units
Total Task Time	seconds
Average Velocity	kph
Distance Traveled	km
Slope/Elevation	Degrees (º)
Seat Vibration	Hzs
Rock Contacts	Frequency of contacts

As for subjective measures, the simulation quality rating scales included the SAE-J1441Subjective Rating Scale for Vehicle Ride and Handling, the Cooper-Harper Handling Qualities Rating Scale, the Cranfield Road Vehicle Dynamic Qualities Rating Scale (CRVDQRS), the Bedford Workload Scale, the Kennedy Motion Sickness Scale (SSQ), and the Acceptability Rating Scale.

The SAE-J1441 is a subjective rating scale for evaluating vehicle ride and handling (Figure 20). The scale is applicable for the evaluation of specific vehicle ride and handling properties, for specified maneuvers, road characteristics and driving conditions, on proving ground and public roads [17]. The 'impact of disturbance' rating is an assessment of the degree to which instabilities are felt by the driver and/or assesses how significantly do disturbances affect the stability of the vehicle and/or affect the driver's inputs (e.g., how does driving over small rocks or holes impact the stability of the vehicle, and does it tweak the driving controls to a minimal or to a significant degree). The rating of "control response" is an assessment of the controllability of the vehicle during a driving task, i.e., the way in which the vehicle responds to driver inputs (e.g., with predictable vs unpredictable responses). Use of the scale includes asking test subjects to provide 2 ratings for each driving task being evaluated, one for 'control response' and one for 'impact of disturbances.' These ratings are independent and are not combined. To pass evaluation for a given task, the ratings for the vehicle must be in the desirable category (6-10) along both dimensions. If either dimension receives a borderline or undesirable rating, then that would indicate a failure for that task [17]. Subjective comments should also be collected for every driving task being scored, in order to provide diagnosticity for mitigating any potential issues related to disturbances or controllability.

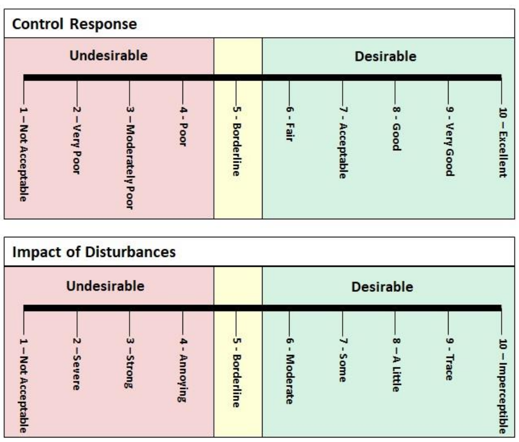


Figure 20. The SAE-J1411Subjective Rating Scale for Vehicle Ride and Handling.

The Cooper-Harper Handling Qualities Rating Scale is a 10-point scale. This scale measures the level of crew accommodation to meet performance objectives (Figure 21). The modified scale uses the same levels as the original Cooper-Harper Handling Qualities Rating Scale [18] but have been modified to handling qualities of the LTV in terms of driving. To choose among the three rating levels, the test driver follows a decision tree. There are different considerations depending upon where the decision tree answers led the test driver [18,19]. A Cooper-Harper rating of 1, 2, or 3 maps to Level 1 where performance is desirable, and the considerations are less discriminating. A Level 2 Cooper-Harper rating of 4, 5, or 6 maps to where performance is considered adequate. At Level 3, the consideration is controllability and dependent on the operators compensation when given the vehicles inadequacies. Lastly, a Cooper-Harper rating of 7, 8, or 9 maps to Level 3 where major deficiencies in performance are noted and controllability of a vehicle is in question. A Cooper-Harper rating of 10 is where control of a vehicle is lost during some portion of the required operation.

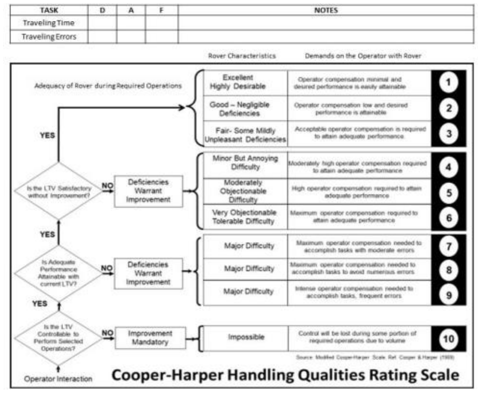


Figure 21. The Cooper-Harper Handling Qualities Scale.

The Cranfield Road Vehicle Dynamic Qualities Rating Scale was developed to emphasize the interaction between the vehicle's dynamic behavior.[20] Based off the Cranfield Aircraft Handling Qualities Rating Scale (CAHQRS) and NASA's Task Load Index (NASA-TLX) Harris, Chan-Pensley and McGarry (2005) [20] took into account the interaction between the vehicle's handling qualities and the task [21,22,23]. With these scales, any interaction of handling qualities and task(s) are incorporated in the testing procedure rather than being recorded and evaluated portion of the measurement instrument [20]. The scale scores six different vehicle dynamic qualities categories using a 1 to 5 scale with bipolar anchor adjectives for each category. The vehicle dynamic qualities categories are broken into sub-categories which are also scored. Table 4 illustrates both the dynamic categories with their assigned bipolar anchor adjectives.

Table 4. *The Cranfield Categories and Anchors [23]*

Dynamic Qualities Category	Dynamic Qualities Definition	Bipolar Anchor Adjectives
Ride Comfort	This refers to the evaluation of the level of comfort when travelling over various road surfaces.	Absorbent/Thumpy Smooth/Harsh
Steering Qualities	This refers to the feedback supplied via the steering wheel. A good steering system should give a crisp and accurate response at the start of a corner and respond proportionally afterwards.	Accurate/Inaccurate Interactive/Uninvolving Responsive/Unresponsive
Performance	This involves the power of the vehicle and is typically reflected by its ability to accelerate.	Frisky/Sluggish Quick/Slow Speedy/Leisurely
Grip	This refers to the absolute lateral grip of the vehicle as a result of the adhesion of the tires to the road surface.	Adhesive/Slippy Grippy/Skiddy

Table 4. *The Cranfield Categories and Anchors [23]*

Dynamic Qualities Category	Dynamic Qualities Definition	Bipolar Anchor Adjectives
Handling Qualities	This refers to the manner by which the vehicle responds to the inputs from the driver.	Firm/Bouncy
		No Body Roll/Tendency to Lean
		Poised/Nervy
		No Oversteer/Tail Oversteer
		No Understeer/Nose Tends to Plough Forward
Ride Composure	This refers to the manner in which the body of the vehicle settles and rides over the road surface.	Controller/Uncontrolled
		Solid/Loose
		Stable/Unstable

Workload is defined as the integrated mental and physical effort (i.e., spare capacity) required to satisfy the perceived demands of the specific task (Figure 22) [24, 25]. The concept of "spare capacity" refers to arousal, time, and fatigue of accomplishing a task. Measurement of workload enables a standardized assessment of whether temporal, spatial, cognitive, and perceptual aspects of tasks and the crew interfaces for these tasks are designed and implemented to support each other. The Bedford Workload Rating Scale is appropriate for assessing workload as it provides anchors for every rating, is familiar to the crew population, and provides a decision gate in which rating above this gate are indicative of workload that is not satisfactory without a reduction in spare capacity.

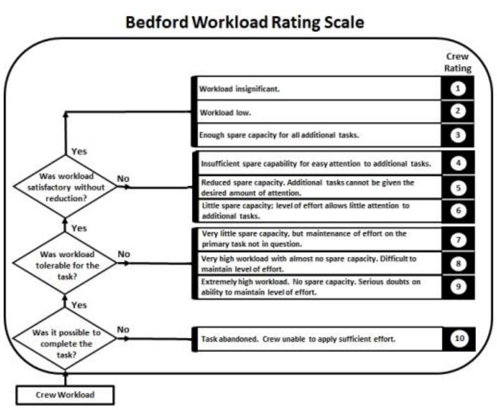
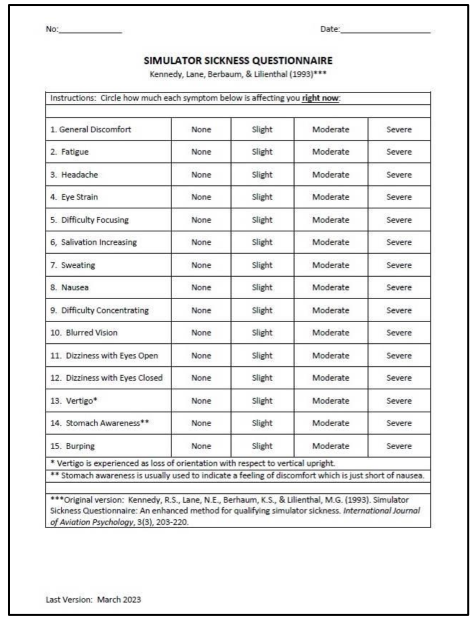


Figure 22. The Bedford Workload Rating Scale.

Simulator sickness (SS) usually occur within the first 10 minutes of a simulation session and frequently can last for several hours afterward [26]. Some ways to reduce SS are to take frequent breaks, adjust the surroundings, make use of customizable settings, use a fan when wearing a VR headset and rejoin reality [27]. This discrepancy is what causes many people to get simulator sickness. There are several ways to assess simulator sickness [28]; however, the most popular method is the Simulator Sickness Questionnaire (SSQ) published 20 years ago by Kennedy, Lane, Berbaum & Lilienthal (1993) [29]. The questionnaire asks the subjects to score 15 symptoms on a four-point scale (0-3) (Figure 23) [30] [31]. The SSQ score is not intended to predict if someone will become ill; however, it does provide a description of the overall simulator sickness score for a given simulation environment [30]. During testing, the SSQ will be given a minimum of three times to the subject: 1) Before the start of a test session, 2) Midway through a test course, and 3) End of a test session.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SIMULATOR SICKNESS QUESTIONNAIRE

Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions: Circle how much each symptom below is affecting you **right now**:

1. General Discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye Strain	None	Slight	Moderate	Severe
5. Difficulty Focusing	None	Slight	Moderate	Severe
6, Salivation Increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty Concentrating	None	Slight	Moderate	Severe
10. Blurred Vision	None	Slight	Moderate	Severe
11. Dizziness with Eyes Open	None	Slight	Moderate	Severe
12. Dizziness with Eyes Closed	None	Slight	Moderate	Severe
13. Vertigo*	None	Slight	Moderate	Severe
14. Stomach Awareness**	None	Slight	Moderate	Severe
15. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

***Original version: Kennedy, R.S., Lane, N.E., Berhaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for qualifying simulator sickness. *International Journal of Aviation Psychology*, 3(3), 203-220.

Last Version: March 2023

Figure 23. The Simulator Sickness Questionnaire (SSQ) [35] [26].

The Acceptability Scale is based on a 10-point Likert scale where the scale is divided into five distinct categories with two numerical ratings within each category to discriminate preferences (Figure 24). The scale was designed, in part, from the Cooper-Harper Quality Handling Scale to have a scale that could quantify how the acceptability of the vehicle designs by the subject using a simple scale. Likert scale data can be considered as either interval or ordinal depending on the presentation of the rating scale to the subject [32]. The Acceptability rating scale is interval because only the rating category, e.g., totally acceptable, acceptable, etc. has a label and descriptor, each individual rating does not have a label. A reasonable interpretation of this scale by a subject is that the distance between the data points along the scale are equal [32]. This is reinforced by the constant width of the scale itself. Interval data can be analyzed with descriptive statistics. The mean and 95% confidence interval will be calculated for the Acceptability rating.

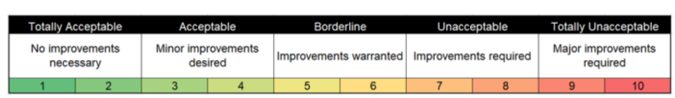

Figure 24. The Acceptability Rating Scale.

5. STUDY RESULTS AND DISCUSSION

All statistical analysis for time, distance, speed, workload and acceptability are reported in medians due to the small population size. The SSQ data used weight averages to calculate a Total Score (TS). Intercorrelation analysis was conducted to compared to the handling quality scales. Since the NASA LTV program will be using the SAE to determine the handling qualities of the commercial vendor's vehicle, the scale will be used for this study to determine if a driving task passed or failed. The SAE-1441J handling qualities score was calculated using the LTV verification success criteria states: "*For success, 80% of the ratings (8/10) collected for each driving task must result in desirable ratings (ratings of 6-10) for both dimensions." (currently under NASA review).*

Simulator Sickness Results and Discussion

Balk, Bertola, and Inman [30] stated : "*Simulator sickness is the result of the discrepancy between simulated visual motion and the sense of movement stemming from the vestibular system*." Meaning the information sensed visually and physical (i.e., movement) must be in sync, if not the human vestibular system will interpret the visual simulation not being synced with the physical motion of the simulator which can cause simulator sickness. To measure simulator sickness (SS), the test team used the gold standard of measuring SS the Kennedy et al. [29] Simulator Sickness Questionnaire (SSQ) [33]. As per the SSQ standards, all 13 test drivers were healthy and fit on the day they participated in the study. The SSQ was administered at the beginning of each course session and approximately after each task or session. Through not by the SSQ authors recommendation, the rational for taking so many SSQ scores was to keep the motion table team as well as the test team alert as to how the test driver was feeling at certain times during the study. However, investigators did use only the scores taken at the end of the simulator session. Using Lane and Kennedy [34] factor analysis studies [34, 35, 36, 37], three clusters of symptoms are identified as 1) Nausea, 2) Oculomotor, and 3) Disorientation. Symptoms that make up the nausea (N) cluster include increased salivation, sweating, stomach awareness, nausea and burping [33] which are all related to gastrointestinal distress [37]. The oculomotor (O) cluster includes fatigue, eyestrain, difficulty focusing and headache [37]. As for disorientation (D) revolves are blurred vision, vertigo, and dizzy with eyes opened and eyes closed [33]. For the overall simulator sickness score for this study, a weighted average was calculated across all test drivers and the three clusters to comprise a total score. The score reflects the severity of the symptomatology for SS and can the team use the Kennedy, Drexter, Compton, Stannely, Lanham and Harm [37] simulator troublesome index (Table 5).

Table 5. *Simulator Troublesome Index[37]*

SSQ Score	Categorization
0	No symptoms
<5	Negligible symptoms
5-10	Minimal symptoms
10-15	Significant symptoms
15-20	Symptoms are a concern
>20	A problem simulator

Using the method of calculation above, the SES motion-based simulator for conducting LTV handling qualities testing in a rough lunar South Pole environment was calculated as a Total Score (TS) across all test drivers as M = 18.98 (SD = 16.75). Therefore, using the simulator troublesome index interpretation, the 18.98 TS falls withing the *symptoms are a concern*. As to where the symptom categories were portion across test drivers, the nausea (N) was the highest (M = 2.23, SD = 2.05) with disorientation (D) being the second most likely cause of SS (M = 1.46, SD = 1.71) while oculomotor (O) was the least likely cause (M = 1.08, SD = 1.25) (Table 6).

Table 6. *Average Scores of the SSQ*

	Nausea	Oculomotor	Disorientation	TS
mean	2.23	1.08	1.46	18.98
SD	2.05	1.25	1.71	16.75
min	0	0	0	0
max	7	4	4	56.1

The secondary objective of the study was to investigate if visually being in a 1/6g environment while driving in a 1g physical environment would affect the test drivers. So could this mismatch in environments invoke simulator sickness. Test drivers conveyed the motion table translated the 1/6 environment well and no issues seem to arise amongst the drivers. In fact, they noted the simulation system performed to expectations by having effective terrain, lighting, vehicle dynamics, motion dynamics, with the sync visual environment. Test drivers acknowledged the performance of the system influence their driving decisions throughout the test even especially when hitting rocks or going through crater which impacted their physical state. Therefore, having the two different gravitational states did not appear to affect the drivers vestibular system.

Test drivers agreed there was little effects of simulator sickness during the Test Track session. They recounted with the short bursts of the individual tasks, they felt comfortable. The short breaks between tasks, due to having to take off the VR headset and score the task, gave the test drivers a small dose of reality before getting back into the VR headset which ease any discomfort, they made have felt. The long traverse course seems to be where test drivers had a difficult time maintaining a level of personal comfort resulting in simulator sickness become an issue. Of the 13 test drivers, five had to stop driving the course at a median of 1,360.1 meters within a median time of 42 minutes and 8 seconds. The majority of the symptoms reported was nausea and stomach awareness. Test drivers specified getting an actual feel for the terrain being bouncy while weaving to avoid terrain features caused significant amount of nausea during the drive. Test drivers believe the prolonged driving time in this type of terrain attributed to the nausea as well. VR headset issues, due to tracking loss, contributed to nausea but affect drivers more from a disorientation factor. They described image flashing or reverse mirroring, the VR screen going black, and graphical glitches all tended to cause dizziness or a disorientation feel amongst test drivers who experienced it. Some test drivers notice the visuals were slight off with the physical motion and jittery. This occurred when the drivers were trying to concentrate on navigating the terrain and the visual simulation seemed to have difficulty coupling with the physical movement causing disorientation. For other test drivers, accelerating the vehicle too fast cause light headiness as well. There were some minor oculomotor affects that test drivers reported. With the visual artifacts and the movement of the table during this long traverse, drivers indicated a amount of both mental and physical fatigue would start to set in fairly quickly; however, they would not really notice this affect until after finishing the full 5 km course. Studies have shown that simulator sickness effects can be cumulative over time [38,39,40,41]; however, researchers agree adaptation to the VR environment appears feasible, but more study is required on this issue.

Handling Quality Scale Results and Discussion

The Spearman Rho Correlation analysis indicated the Cooper-Harper and SAE-1441J correlated very well against each other and the Bedford Workload Scale; however, the Cranfield exhibited a weak correlation when compared against the other scales. With this in mind, the NASA LTV program has proposed using the SAE-1441J to determine the handling qualities of the commercial vendor's vehicle since this scale examines vehicle dynamic qualities more accurately compared to the others tested. The scale will be used for this study to determine if a driving task passed or failed. The SAE-1441J handling qualities score was calculated using the LTV verification success criteria states: "*For success, 80% of the ratings (8/10) collected for each driving task must result in desirable ratings (ratings of 6-10) for both dimensions." (currently under NASA review).* As previously discussed, the SAE-1441J is a subjective scale for evaluating vehicle ride and handling. Test drivers gave two ratings. One to assess the controllability of the vehicle while driving (control response) and the second for assessing the degree to which the instabilities are felt by the driver and vehicle on surface conditions (impact of disturbance). Results exhibit that six out of eight total driving tasks passed (Table 7). The crater rim (crabbing) on mixed terrain task failed. Test drivers felt like there were a lot of inconsistencies with how the controller would correlate the inputs to the vehicle movement causing the driver to input multiple inputs resulting in a tail oversteer situation. This caused the vehicle to spin out of control, especially when the rear wheels contacted with rocks. The other driving situation which failed the SAE validation was driving the 5 km long traverse. Test drivers conveyed the vehicle did what they expected with the given terrain; however, it was not a joy to drive in the rough lunar South Pole terrain. Contact with rocks made the vehicle bounce while trying to weave to avoid craters. The "finicky" nature of the hand controller caused drivers to either oversteer or understeer caused driver overcompensation with abrupt directional changes making the overall ride with the vehicle motion very uncomfortable and overall unpleasant.

Table 7. *SAE Scores Across All Test Drivers*

Driving Task	Terrain	Drivers Scores per Task		Pass/Fail
		Pass	Fail	
Acceleration/Max Speed/Brake	Straight Level	100%	0%	PASS
Crater Field Avoidance	Mixed	92%	8%	PASS
Constant Lateral Turn 360º	Mixed	92%	8%	PASS
Crater Rim (Crabbing)	Mixed	77%	23%	FAIL
Down Slope	Mixed at 15º	92%	8%	PASS
Cross Slope	Mixed at 20º	100%	0%	PASS
Up Slope	Mixed at 15º-20º	100%	0%	PASS
Long Traverse	Mixed	62%	38%	FAIL

Test Track Task Results and Discussion

The Acceleration and Maintaining Max Speed Task was broken into two segments:1) 0 kph to max acceleration speed and 2) maintaining max speed. These speed tasks test the vehicle's ability to get up to speed and maintain the max speed for a pre-determined distance. The Braking and Sliding was likewise broken into two segments: 1) First Brake at Max Speed and 2) Sliding Distance to Vehicle Stop. The Crater Field Avoidance Task is a classic object avoidance task. With the Constant Lateral Turn 360-Degree Task, the vehicle is tested to see if it can accomplish a 360-degree turn under a pre-determine speed while maintaining a pre-determine distance in a lateral turning mode such as Ackermann. The Crater Rim Driving Task is the only crabbing mode driving task the drivers accomplish on the Test Track Course examining the vehicle's ability to drive around a crater rim with the nose of the vehicle standing centered on the crater's center. Finally, three slope driving tasks that exercises the vehicle's handling for slopes down/cross/up to 20-degrees in nature. Drivers were required to maintain a pre-determine speed, avoid terrain features, and to assess if the vehicle slips during these events.

Acceleration and Max Speed on Straight Level Terrain

This is the first LTV model, virtual or physical, in a 1/6g lunar environment which has accomplished any road handling tests of any kind. From a lunar perspective, Apollo 15 reported when they accelerated the LRV on the lunar surface "*it was smooth with very little wheel slippage."* [42]

For this study, test drivers drove a 300-meter straightforward distance with flat, level terrain devoid of any obstacles. Starting at a dead stop the driver would push the control to its max as the rover came up to the top speed of 12 kph. Once the top speed was achieved, the driver would maintain that speed for 300-meters. The calculated median performance statistic for this task indicated in took test drivers 2.5 seconds and 5.17 meters at a ramp up speed of 7.42 kph to get the vehicle from 0 to 12 kph (max speed) (Table 8). During the acceleration event, drivers reported that at first full deflection of the hand controller to the first turn of the wheels they could feel a little jolt or jerk from the vehicle as the wheels gripped the lunar surface and on occasion, they felt the vehicle do a little skid due to how fast each wheel module gripped the ground. This could be due to wheel alignment as well as a slight delay in the response of the hand controller. While accelerating some drivers noted the initial acceleration was good but not necessarily powerful. Some felt the vehicle took some time to for the vehicle to get up to speed and it felt a little sluggish indicating that the terrainmechanics model in the simulation was functioning properly. Others stated it took only minimal time for the vehicle to quickly obtain max speed.

Table 8. *Acceleration to Max Speed Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	2.50	5.17	7.42
SD	3.76	42.59	1.51
min	2.30	4.89	3.35
max	15.30	159.28	7.63

For the second portion of the task, test driver, once at 12 kph, had a calculated median performance across drivers of 11.7 kph maintainable speed for 311.6 meters for 97 seconds (Table 9). The majority of the test drivers found maintaining the max speed was simple and easy. Once at max speed some drivers reported they felt the vehicle was going slower than what was indicated on the display. They reported the vehicle response was respectable; however, the hand controller was not super sensitive in responding immediately. It was observed the speed of the vehicle seemed to deaccelerate/accelerator too fast with small hand controller movements adding to the difficulty of maintaining a constant speed and feedback in the hand controller was needed. This could be caused by dead zones issues with how the hand controller was initial setup for testing or hand fatigue from manually keeping the hand controller at max deflection. Overall driver workload for this task was consider the Bedford Workload Scale as a Level 1 (Mdn = 1) where there is sufficient spare capacity of the driver for all desirable additional tasks. Drivers reported the task was straight forward with smooth terrain. They had more than enough spare capacity to look around and observe the landscape as well as monitor their speed on the display.

Table 9. *Straight Level Max Speed Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	97.00	311.67	11.77
SD	108.35	58.97	3.16
min	90.00	140.99	3.50
max	484.00	327.63	12.00

Braking/Sliding Distance Task on Straight Level Terrain

Apollo 15 tested braking of the LRV on the Moon reporting: "*Braking was positive except at high speeds. Speeds under 5kph braking appeared to occur in approximately the same distance as with the 1g trainer. Braking was less effective when the vehicle [LRV] was in a turn, especially at high speeds*." [42] For a lunar vehicle, the braking task has the vehicle at max speed of 12 kph, at a certain distance, in this case 300-meters. The driver braked the vehicle hard and held the brake until the vehicle came to a full and complete stop. The first portion of this task was first brake contact to vehicle stop. The median performance stats indicated at 11.9 kph the vehicle took 13 seconds and 3.86 meters to come to a complete stop (Table 10). Drivers reported the vehicle stopped quickly and the hand controller seems responsive during the braking action. Some indicated too quickly as "super abrupt," "twitchy," and "harsh." Some drivers observed the 1/6-g lunar gravity environment affected how long it took the vehicle to stop. Workload for braking was again enfolded into the acceleration and straight score which was deemed the driver had enough spare capacity with the workload being insufficiently affected.

Table 10. *First Brake to Full Stop Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	13.00	3.86	11.99
SD	3.06	0.93	2.92
min	9.00	0.58	1.44
max	20.00	4.31	12.20

Investigators were also interested in the amount of time the vehicle slide to a full stop once the brakes were fully engaged. Apollo 15 did a similar test while on the Moon and stated: "*From a straight-line traveling at velocities of approximately 10 kph on a level surface, the vehicle [LRV] could stop in a distance of approximately twice the distance that was experienced in the 1g trainer*." [42] Unfortunately, there are no recorded accounts of the braking distance for the LRV 1-g trainer. The parameters for vehicle sliding were from when the vehicle wheels stopped until a distance was no longer being recorded. Median performance data indicates the vehicle slide for 0.24 meters for 2 seconds at a speed of 0.58 kph (Table 11). Investigators noticed in the simulation data the vehicle tended to hop during the slide, much like a pebble skipping across a lake (Mdn = 5 hops). Drivers conveyed the vehicle was bucking and rocking a lot. They felt the vehicle "jitter" or skidded as the wheels were trying to grasp the terrain. Some possible rational for this "hopping" occurrence could be the active suspension taken hold as the vehicle came to abrupt stop or the wheels grasping at the terrain. The motion table itself may have affect this event as well. Drivers did note that it seemed the motion table was trying to accommodate for the sudden shock of breaking at max speed causing it to rock and wobble as it was trying to catch up to the actual event.

Table 11. *Braking Sliding Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	2.00	0.24	0.58
SD	0.58	0.09	0.05
min	1.30	0.11	0.50
max	3.80	0.49	0.65

Crater Field Avoidance Task on Mixed Terrain

Crater and rock fields are lunar terrain features crew could interact with when driving a rover on the lunar surface. In fact, Apollo 15 noted this very fact during their mission report: *"Obstacle avoidance was commensurate with speed. Lateral skidding occurred during any hard over or maximum rate turn above 5kph. Fragmental debris was clearly visible and easy to avoid. The small, hummocky craters were the major problem while negotiating the traverse."*[42]. Test drivers had the basic same reaction; however, the lighting conditions on the South Lunar Pole is much worst. The mechanics of the task were these test drivers had to go through a crater field located at a scientific area of Bear Paw. The drivers had to get through the crater field without hitting any craters for approximately 300-meters. Rocks of various sizes were distributed by statistical analysis around the craters. The speed through the field was at the drivers discretion. Median performance data showed test drivers taking 271.5 seconds to traverse a 300.5-meter crater field at a speed of 4.2 kph (Table 12). This concurs with what Apollo 15 reported; "*For obstacle avoidance, the optimum technique was to slow [the LRV] down to below 5 kph*."[42] With the short type turns to avoid craters, test drivers noted the hand controller responsiveness was good; however, the wheel modules appeared to have some difficulty pointing in the correct direction. Using a yaw, twisting motion on the hand controller to make turns had some drivers overcompensate the steering of the turn in order to avoid a crater or stop. This led test drivers to state that maneuvering around the rocks and craters during this task was particularly problematic. With the vehicle in Ackermann steering, most drivers could avoid the craters sufficiently. However, in the crab steering mode, drivers sensed the vehicle had some difficulty adapting especially if a rock or crater rim was contacted. The behavior between switching from Ackermann to crab mode made the vehicle and hand controller feel unnatural to the driver and did not match the behaviors of the vehicle. This unnatural sensation could be caused by the vehicle's steering "gimbal" striking its hard stops and then uncoiling again. When the vehicle wheels contacted either rocks, elevation changes, or craters, drivers stated they started to wrestle with the controls. Turning became very challenging in tight places around craters and the vehicle tended to drift backwards or spin especially if the driver contacted a rock or crater rim. This type of contact was the cause of drivers fighting to maintain stability and control. Workload was scored at the edge of Level 1 (Mdn = 3) meaning the drivers had enough spare capacity for all desirable additional tasks. As a solo driver the workload was manageable but most test drivers attention was spent on dodging craters and paying close attention to the terrain to plan out a route. To make this task easier, the majority of the drivers reported they would want a second person as a co-pilot to off load the navigation portion of the task while driving through a crater cluster and monitor speed.

Table 12. *Crated Field Avoidance Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	271.50	300.56	4.20
SD	253.68	45.00	1.44
min	108.00	139.25	2.16
max	1059.00	306.25	7.70

Constant Lateral Turn 360⁰ Task on Mixed Terrain

The constant speed 360-degree turn exercises the capabilities of the rover's Ackermann steering mode when inspecting a lander or habitat on the lunar surface. The driver starts at a predetermined point and speed. Test drivers are to go around the lander while avoiding craters and keeping within a 10-meter distance of the lander. Median performance stats demonstrate it took test drivers 126 seconds to traverse 165.4 meters around the lander at 4.5 kph (Table 13). The act of turning was reported as "spot on" and drivers did not have to turn the controller much to get the turning motion and feedback from the vehicle. Some test drivers did indicate the mapping of the hand controller could be improved for a task such as a 360-degree turn. They observed it required a significant amount of wrist torque which was not intuitive for Ackermann steering. Maintaining speed was another factor of concern among test drivers. A majority of drivers stated it was very difficult to maintain a constant speed especially at a low speed. First, the hand controller input for speed seemed "jumpy" in its response. Drivers perceived it was too easy to punch the vehicle forward and increase speed. Additionally, trying to manually change the speed +/- 1 kph was tricky. This could be due to controller mapping as a driver had to twist or yaw the controller to turn the vehicle while at the same time pushing the controller forward to input speed. The more yaw force put into the controller would cross couple into a higher speed than anticipated. Remapping the turning aspect of the controller as a roll function instead of a yaw function would have improve the wrist fatigue. Additionally, it was observed by drivers that a slightly faster speed helped to maintain maneuverability of the vehicle in the turn. Terrain features, such as a crater rim or rocks, affect the speed. A solution to the speed issue would be to employ a cruise control or a maximum rate limiter to aid the vehicle driver in maintaining an exact speed. Workload for this task was considered low and manageable (Mdn = 2).

Table 13. *Constant Speed Lateral Turn Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	126.00	165.37	4.50
SD	170.18	52.05	2.53
min	53.00	21.96	0.65
max	722.00	259.34	10.51

Crater Rim Task (Crabbing) on Mixed Terrain

Craters are interesting terrain features. They can be very small to kilometers in diameter, young with steep sloped walls rims or old with fading, shallow slopes. Test drivers were asked to drive a recon task of a 15-meter diameter crater near a landing site. The slopes of the crater chosen were smooth. This was to test maneuverability of crab steering mode and the vehicle response to the is specialty mode. The object was to keep the rover nose pointed to the center of the crater while driving around its rim and avoiding any other smaller craters and rocks. Performance data demonstrates median stats across drivers it took 174 seconds to traverse 74.8 meters around a 15-meter crater as a speed of 1.76 kph (Table 14). Some drivers were able to crab with ease; however, they did observe that maintaining speed and distance around the crater rim took a lot of focus. This could be due to the low angle lighting conditions of the lunar South Pole as some drivers noted it was hard to tell where the edge of the crater rim actually was located. Furthermore, drivers reported the hand controller, though responsive, was too responsive which caused control issues. Though a majority of drivers thought crater rim driving was acceptable, moving through rocky terrain around a crater was difficult in the crab steering mode. They felt like there were a lot of inconsistencies with how the controller would correlate the inputs to the vehicle movement. They reported feeling a delay between the controller inputs which caused them to constantly fight the controller to regain vehicle control and to prevent the vehicle from spinning out of control during the task especially when the rear wheels made contact a rock or a smaller crater rim. This caused the driver to put in multiple inputs to the hand controller that would result in a tail oversteer situation. This, in turn, caused the driver to feel the vehicle's wheels, as well as the vehicle's speed, were not receiving the proper inputs being made by the driver. Thus, making the vehicle go rogue as the driver tried to regain control. The more the driver fought the controls to correct the issue the more the situation got worst. This could be due to the limitations of the steering "gimbal" hitting its hard stops of travel and then unwinding again making the steering actuators speed feel unnatural and confusing to the driver. One solution, a driver reported, was using a cruise control function for the speed taken out one of the hand controller manual inputs. Some drivers confessed they thought most of the issues with doing this particular task was pilot error. It depends on how the hand controller is mapped as there is a lot of movement the driver has to make to accomplish this task. Thus, the rational for using a task to drive out the response and maneuverability of driver, hand controller and vehicle in the first place. The majority of the drivers noted there was a big learning curve with this activity. It takes a lot of practice to be about to find the "sweet spot" for crabbing with any hand controller. The crater rim (crabbing) driving pushed the workload into a low Level 2 range (Mdn = 4) indicating the driver has insufficient spare capacity for easy attention for any additional tasks. Test drivers described that with this task there were multiple elements which need one's attention such maintaining speed, rim distance and object avoidance. Some noted the vehicle felt out of control due to multiple control inputs. Lighting was also causing some issues with crater rim visibility taking up a lot of driver focus. To improve this situation, drivers noted a co-pilot would be very helpful for monitoring rim distance, speed, and stray objects.

Table 14. *Crater Rim(Crabbing) Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	174.00	74.86	1.76
SD	52.39	38.66	1.19
min	75.00	44.89	1.08
max	225.00	177.36	5.04

Down Slope Task on Mixed Terrain

Slopes will be encountered on a lunar mission. Every Apollo LRV mission had slopes and the astronauts wrote about their experience. Apollo 16 reported: "*The best way to negotiate slopes in the rover [LRV] is to go straight up and straight down*." [43] The Apollo 17 crew noted: "*Coming down these slopes [of 20 degrees], the vehicle was operated in a braking mode with no indication of brake-fading or feeling that the rover [LRV] was uncontrolled*." [44] Test drivers with the LTV in a motion simulator completed a down slope task. The terrain did have some lightly scattered rocks and craters of varying sizes. Sun condition was up sun, and the down slope task was intended to be a 20-degrees; however, due to some discrepancies with the motion table angle and the electronic test conductor display, the slope was off by 5-dgrees meaning the test drivers only felt a 15-degree down slope instead of a 20-degree slope. Interesting, this anomaly only occurred in the down slope task and not in the up or cross slopes tasks. The medina performance calculations indicate at a distance of 232.9 meters going 5.67 kph it took drivers 145 seconds to complete this task. Speeds while descending a down slope speed varied from 5 to 10 kph for the Apollo LRV astronauts [42,43,44]. Median performance stats for this tasked showed a speed of 5.67 kph going down a 232.9-meter slope taking 145 seconds (Table 15). Majority of the test drivers had no issue with begin able to control the rover in a down slope configuration. The controls felt responsive. Maintaining speed, however, was a little more challenging. Drivers indicated that the variability in speed was caused by rocks and craters that had to be avoided. This made the vehicle somewhat "bouncy" going down slope and some understeering was reported. Drivers also reported feeling driving a down slope, one gets the sense of the vehicle is drifting making it very easy to lose control of the speed with minor terrain disturbances. The up-sun angle distracted drivers from seeing rocks and craters. This concurs with the Apollo LRV crews stating: "*Forward visibility driving towards the zero-phase direction [up sun] [is where] washout [occurred making] obstacle avoidance difficult*". [42]. Workload for the down slope driving task was considered low (Mdn = 2) as drivers felt like they could divert their attention to other things or perform additional tasks if require during this task.

Table 15. *Down Slope Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	145.00	232.99	5.67
SD	308.73	14.37	2.25
min	75.00	216.95	0.72
max	1246.00	272.20	8.10

Cross Slope Task on Mixed Terrain

For any type of off-road driving, cross slopes can become tricky. The Apollo 16 crew noted: "*Going cross-slope or parallel to contour lines produces right or left rolls of 10 to 15 degrees …. Is very uncomfortable, even though the vehicle [LRV] was never unstable during cross slope driving*." [43] This was reiterated the Apollo 17 LRV crew who reported: "S*ide slopes were negotiable, but not necessarily comfortable and engendered a great deal more caution*." [44] The Apollo 17 crew did believe the LRV could negotiate cross slopes of 20 to 25 degrees these types of cross slope operations never become comfortable [44]. The cross-slope task for this study did involve a varying slope up to 20-degrees over a 300-meter distance; however, due to the fact the motion table had only gotten certified for a single seat, the test driver was seated in the center of the platform and reportedly did not feel the same discomfort on a cross slope as the Apollo 16 and 17 LRV crews experienced. Median performance indicated it took 211 seconds at a speed of 5.72 kph to traverse a 332-meter cross slope (Table 16). Both Apollo 16 and 17 LRV crews reported speeds on a cross-slope can be the same as on up-slopes with one exception as stated by Apollo 17's LRV crew: "*Comparable velocities could be maintained on [cross] slopes unless crater avoidance became necessary*." [44] Test drivers reported they were pleasantly surprised how well the LTV handled on a cross-slope. Most found the vehicle response quick, and pitch or angle did was not a factor with control. However, some drivers noticed the vehicle tended to want to turn down slope. They indicated with a left roll cross-slope, they had to maintain a little pressure on their arm to apply a small amount of force on the hand controller to keep the vehicle progressing straight across the slope. Apollo 15 concurred stating: *"…velocities could be maintained obliquely on slopes with the downhill wheel tending to dig in and speed was reduced for safety."* [42] As with the down slope task, the workload for the cross slope driving task (Mdn = 2) indicating workload was considered low.

Table 16. *Cross Slope Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	211.00	332.00	5.72
SD	78.91	59.97	3.00
min	92.00	297.82	3.06
max	372.00	485.01	12.13

Up Slope Task on Mixed Terrain

Up slope driving received a great amount of attention from the Apollo LRV crews. Apollo 15 noted: "*Driving directly up-slope on [a] soft surface material, maximum velocities on 10 kph were maintained."* [42] This concurs with an Apollo 17 observation: "*Driving up slope on soft surface material at the Apennine Front maximum velocities of 10 kph were maintained*."[44] However, Apollo 16 sums it up best: "*At Stone Mountain, the vehicle [LRV] climbed very steep slopes with the pitch needle pegging at 20-degrees. The only way the crew could judge up-slope vehicle movement in the lunar environment was by the reduction in speed of the vehicle as it climbed the slope*." [43] However, Apollo 15 noted: "…[going down sun] *the problem encountered was recognizing the subtle, subdued craters directly in front of the vehicle [LRV]. In general, 1-meter craters were detectable until the front wheels hand approached to within 2 to 3 meters*." [42] The up-slope the test drivers performed on the motion table was approximately 20-degrees and a distance of 300-meters with terrain features including rocks and craters. The sun angle was down-sun meaning the sun was at the backs of the drivers. Performance medians indicate for a distance of 243.12-meters going 5.51 kph took 136 seconds across all test drivers (Table 17). This seems to concur with the reported experience from the Apollo LRV crews with the LRV slowing down the steeper the slope rose as Apollo 17 noted: "*Slopes of up to 20-degrees were easily negotiated in a straight-ahead mode. While climbing such slopes at full power, the vehicle [LRV] decelerated to a constant speed of 4 to 5 kph."* [44] First and foremost, the drivers stated that while driving the up-slope task on the motion table, they could feel themselves being pushed back into their seats. Due to the terrain, the drive up-slope was jerky, and the vehicle tended to bounce over rocks and craters. The disturbances in the terrain would affect the driver's ability to control the hand controller input as this would cause jostling of the hand on the controller. Additionally, some drivers noticed the vehicle had a propensity to "jump up" causing the vehicle to increase front end pitch as the back wheels continue to drive the vehicle. Driver conveyed their workload was low and manageable (Mdn = 2) as their workload was tied to the terrain they traversed.

Table 17. *Up Slope Performance*

	Time (in sec)	Distance (in meters)	Speed (in kph)
median	136.00	243.12	5.51
SD	82.90	27.96	2.70
min	78.00	198.54	3.10
max	359.00	289.02	10.62

Long Traverse Course Results and Discussion

The long traverse was a 5 km course which incorporated all of the test track task elements within a single course. The coursed started from the ABC to the lander site on the lunar South Pole. Test drivers got to experience it all, from shadowed areas to high density cratered areas with varying sizes of rocks, to going up-sun taxing the driver's visibility, to slopes of various angles. This was to give the test driver the feel of what a nominal lunar rover traverse would be experienced by the astronauts. It should be noted of the 13 test drivers, only 5 made it through to the landing site. Two drivers had hard cutoff times due to scheduling, while one actually crashed the motion table, and the other 5 got simulator sickness and could not continue. The overall median performance across all test drivers shows 2,008.6-meters were traverse at a speed of 5.11 kph taking 1,438 seconds. The median performance for the five test drivers who completed the course indicated a distance of 5,071.12-meters were traveled at a speed of 6.62 kph taking 2,813 seconds (Table 18). The majority of drivers reported while on this course the vehicle did what they expected making drivers felt good about how the vehicle handled the terrain of crater clusters and rocks; however, it was not a joy to drive in the rough lunar South Pole terrain. There was a lot of situations where the drivers had to weave in and out of craters to avoid contacting them which made handling a little intensive with some overcompensation and abrupt changes in vehicle motion making the overall ride uncomfortable. This made some of the hand controller inputs "finicky" causing either oversteer or understeer depending on the situation. Some drivers drove the entire course in Ackermann and noted this steering mode was intuitive for the task. But some drivers used a combination of Ackermann and crab mode and could switch steering modes within a second and still have the hand controller response well. While others noted that the crab function seem to perform oddly making the vehicle due sudden rotations as it hit rocks. There were instances where the terrain tended to push the vehicle around and would bounce the driver around sometimes violently on the motion table. First, due to the South Pole lighting it was difficult for driver to see rocks to avoid them, and they noted it was difficult to judge the rock size. A lot of time was used having to stop the vehicle to assess the terrain ahead. The number of craters also became an issue. If the area had a large number of craters, then control became a bit more challenging. Driver reported they were constantly changing direction and noticed the vehicle slipping. For example, one driver stated that when the vehicle was hit something or was coming out of a shallow crater, the vehicle wheels felt like they would "get a bit of air" and would make the vehicle skid or fish tail when the wheels came back into contact with the lunar surface. This was also noted with the Apollo 15 LRV crew noting: "*The 'floating' of the [suited] crewmember in the 1/6g filed was quite noticeable in comparison to [the] 1g simulation…. Making it difficult to tell how many wheels were off the ground at any one time*. " [42] Overall, the drivers who completed the entire course indicated the pilot had to study their terrain and be very aware of the hazards. Weaving and bouncing around for approximately an hour made even the heartiness driver somewhat nauseous and fatigued. However, all drivers noted it could be a tolerable task. Driver workload for this task was driven by the complexity of the course (Mdn = 4) where there is insufficient spare capacity of the driver for easy attention for additional tasks. Most looked at the display but did not have the mental capacity to do much navigation as they were extremely focused on the hazards of the terrain. Therefore, all the test drivers wanted an additional person to aid in the navigations and obstacle avoidance as they drove the course. For this task, a test conductor did step in as the co-pilot. They noted this task could be done solo but would take a lot more time as the driver would have to go slower. Furthermore, all drivers felt their workload scores would have decreased to a Level 1 with a knowledgeable co-pilot at their side.

Table 18. *Long Traverse Performance*

	All Test Drivers			Test Drivers Completed Course		
	Time (in sec)	**Distance (in m)**	**Speed (in kph)**	**Time (in sec)**	**Distance (in m)**	**Speed (in kph)**
median	1438.00	2008.66	5.11	2813.00	5071.12	6.62
SD	1002.87	1926.52	1.70	561.75	57.11	1.21
min	379.00	142.73	1.37	2320.00	5017.24	4.93
max	3699.00	5165.88	7.92	3699.00	5165.88	7.92

6. CONCLUSIONS

From the first lunar rover simulator in the late 1960s to today's SES Motion Table at JSC, developing these types of systems for lunar driving is a valuable asset for system engineering and training especially when the real environment is not accessible. This funded NASA grant was to develop a motion table system for NASA to support the lunar surface mobility development and astronaut training. This motion simulator is a first-in-class unique simulation platform having the capability of testing all the lunar rover design requirements. The project built a full up motion system architecture, implemented VR integration with lunar surface rover aspects, reference design rover controls for simulation driving, washout tuning for human motion queuing and acquired a human rating certification for the system.

Evaluating the precision of the motion table system performance with a rigorous driving study, revealed some of the capacities which need improvement including further refinements in the washout process to enhance the lunar driving experience. Investigators were able to gain an understanding into the handling qualities of a lunar rover in the 1/6g lunar environment. The study showed that having a visual simulation where everything in the virtual environment is at lunar gravity while the test driver is physically feeling a 1g environment tended to not have an effect of the test driver. However, having visual mismatches, graphical glitches, image flashing, image mirroring due to loss of tracking with the VR headset did affect and cause some simulator sickness in half of the test drivers. Agreement among test drivers that the Test Track session had little effect on simulator sickness was encouraging noted the short duration of the task and the breaks out of the VR headset. The long 5km traverse is where the majority of the simulator sickness occurred due to the bouncy rocky terrain and the constant weaving to avoid craters.

The correlation analysis indicated the SAE 1441J Subjective Rating Scale for Vehicle Ride and Handling method was strongly correlated with the Cooper Harper Handling Qualities Rating Scale, as well as with the Bedford Workload Rating Scale, which was in-line with expectations, bolstering use of the scales in vehicle assessment.; however, the Cranfield Road Vehicle Dynamic Qualities Rating Scale was only weekly correlated with the other handling quality scales, though it did provide additional insight into design relevant considerations. These findings support NASA's decision to use the SAE 1441J scale for verification of rover handling quality requirements as a ground vehicle alternative to use of the Cooper-Harper Handling Qualities Rating Scale (which rather than being tailored for ground vehicles, was instead developed for use in aviation vehicle assessment). As noted, the Cranfield scale may offer more value in the design and development phase of a vehicle, though it does not appear to be suitable for NASA verification testing.

For the first time in lunar rover history, researchers collected handling qualities data in simulated motion table environment to understand what driving characteristics can be seen in driver performance. Using a test track course, which was developed from the automotive industry, military standards, off-road industry and the aerospace community, the test track concept proved successful. Timing, distance, and speed data along with subjective data gave researchers the unique opportunity to collect handling quality on a lunar rover in a 1/6g lunar simulated environment. Driving tasks, such as acceleration to max speed, maintaining max speed on straight level terrain, braking characteristics, obstacle avoidance, lateral constant 360-degree turn, crater rim driving using crabbing, up/cross/down slope tasks, concurred with what little historical Apollo LRV driving data from the lunar surface that was available. Indicating, the simulation model, though not perfect, is close by producing data that matches actual lunar data (Table 19).

Table 19. *LRV Speeds [42,43,44] vs. NASA LTV Speeds (in kph)*

Rover Missions	Flat/Level /Straight Terrain	Up Slope	Down Slope	Cross Slope	Obstacle Avoidance
A15	13.0	10.0	10.0	10.0	5.0
A16	14.0	5.0	7 to 8	5.0	5.0
A17	12.0	4 to 5	5.0	5.0	5.0
IRAD	**11.7**	**5.5**	**5.7**	**5.7**	**4.2**

Test drivers who were able to complete the 5 km long traverse course, conveyed general knowledge of how a crewmember would feel after a complex traverse path noting both physical and mental fatigue. If this can be replicated in future evaluations, then mission planners will need to re-evaluate how to plan mission timelines. From a handling qualities point of view, the test track collected design development data about the interactions and performance between the vehicle and the driver, while the long traverse tended to show more operational type data, such as fatigue.

Future plans for the motion table system at JSC includes designing and building a dual seat rover cockpit with two conceptual hand controllers for continued lunar rover handling qualities testing. Replacing VR headsets with wrap around monitors for future unpressurized as well as pressurized suit crewmember testing. Lastly, to develop a 1g calculation method to enhance the calculation of the motion table using a known terrestrial environment (i.e., the JSC Rock Yard).

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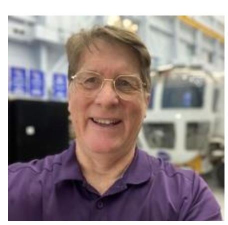
BIOGRAPHY



Harry L. Litaker, Jr. *is a Senior Human Factors Design Engineer and Project Engineer for the Aerospace Corporation at Johnson Space Center, Houston, Texas. Mr. Litaker works with the Software, Robotics, and Simulation Division and the Human Systems Engineering and Integration Division of the Human*

Health and Performance Directorate at Johnson Space Center. He received his Bachelor of Science degree in Communications from Western Carolina University and a Masters in Aeronautical Science degree from Embry-Riddle Aeronautical University in Human Factors Engineering and Safety Engineering. He has extensive human factors experience in spacecraft design, aviation and human-machine interfaces, virtual reality simulation testing and communications. Currently, Mr. Litaker has been the human factor lead for the Lunar Surface Mobility project, the Low-Latency Teleoperations (LLT) study, the Small Pressurized Rover (SPR) and Unpressurized Rover (UPR) project, the Lunar Terrain Vehicle (LTV) project, and the Broad Agency Announcement (BAA) Cislunar Habitat testing. He has conducted human performance and design research studies in such exploration analog environments as the Desert Research and Technologies Studies (DRATS), the NASA Extreme Environment Mission Operations (NEEMO), NASA's Space Environment Analog for Training, Engineering, Science, and Technology (SEATEST), and in partial gravity simulators.

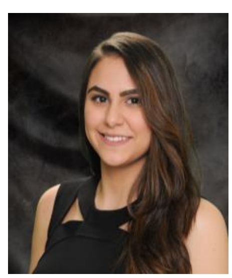
Dr. Gordon A. Vos *works at NASA's Johnson Space Center as the Human Factors Technical Discipline Lead applying human factors expertise to the design, development, testing, verification, and evaluation of vehicles, habitats, equipment, and systems in order to promote human performance and safety for the astronaut crew in the space environment and the ground crew on Earth. He supports a variety of NASA human spaceflight development programs and projects including the NASA Engineering & Safety Center (NESC), the Commercial Crew Program (CCP), the Human Research Program (HRP), Autonomous systems and Operations (ASO), Extra-Vehicular Activity (EVA), Gateway, and the Human Landing System (HLS).*

Asher P. Lieberman *is the Systems Engineering Simulator Manager at NASA Johnson Space Center in the Software, Robotics and Simulation Division in the Simulation and Graphics Branch. He earned a Bachelor and Master of Electrical Engineering Degree from New Mexico State University. He has developed energetic systems including propulsion testing and robotics that enable and expand human spaceflight for NASA. His work has included telemetry and control for propulsion system testing in simulated altitude chambers, and development of dynamic test systems used for simulating exploration environments with robotic systems. Managing the Systems Engineering Simulator facility allows NASA to fly and train the missions of tomorrow, today. Placing humans in simulated environments enables NASA engineers, astronauts and program managers to make better decisions on how to architect and execute missions. Mr. Lieberman is passionate about creating new technology and partnering with academic, government and commercial sectors to help NASA accomplish its purpose while helping humanity on Earth.*

Lee K. Bingham *received a B.S. in Computer Engineering and a M.S. in Electrical Engineering. Lee began his career at NASA Johnson Space Center in 2016 with the Software, Robotics and Simulation Division and has contributed to simulation and visualization development for the NASA Exploration Systems Simulations (NExSyS) team and the Virtual Reality Training Lab. He is the lead of HITL Test Simulation and Graphics Team, the Digital Lunar Exploration Sites Unreal Simulation Tool (DUST) and the Lunar Surface Mixed-Reality and Active Response Gravity Offload System (ARGOS) projects.*

Vanessa L. Jones *is a Human Factors Engineer for the University of Houston Clear Lake working with the Human Health and Performance Directorate at the NASA Johnson Space Center. She holds an M.S. in Cognitive Psychology with a Human Factors focus from the University of Houston- Clear Lake as well as a B.S. in Psychology from Morehead State University. Ms. Jones has experience in human factors research and usability testing and has contributed to projects relating to Virtual Reality (VR), Augmented Reality (AR), User Interface (UI) consistency, Ergonomics, Scale Validation and User Experience research.*

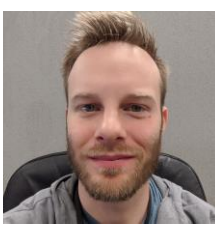
Nadia Scharunovych *is a Technical Mechanical Engineer for KBR working with the Center of Design and Space Architecture of the Human Health and Performance Directorate at Johnson Space Center. She received her Bachelor of Science degree in Mechanical Engineering from Colorado School of Mines. Nadia has experience in human factors in spacecraft design. robotics, and rover design. Nadia is working as a designer for the Lunar Terrain Vehicle (LTV).*



Athena A. Frangoudis*, is a Human Factors Space Architect for JES Tech working with the Human Systems Engineering and Integration Division of the Human Health and Performance Directorate at Johnson Space Center. She received her Bachelor of Architecture degree from Pratt Institute. She previously worked* *as an architectural and interior designer enabling her to envision human centric design in space applications. She has experience in habitat design, human machine interface design, and mockup prototyping. Ms. Frangoudis has worked on projects such as the Lunar Terrain Vehicle (LTV), Small Pressurized Rover (SPR), and Gateway.*

Terence J. Gelo *is a Houston-based industrial designer with a background spanning human factors, engineering, product design, and project management. After studying Industrial Design at the University of Houston, his work with consultancies and consumer product companies resulted in product lines that are available in retailers across the U.S. and abroad. In 2019, Terence was invited to teach sophomore industrial design studio at his alma mater. Concurrent with this he worked at Taxa Outdoors, managing the design and engineering of NASA-inspired camping habitats to redefine the recreational vehicle industry. Currently Terence works as Senior Industrial Designer for NASA, contracted through KBR. Working on-site at Johnson Space Center in the Center for Design and Space Architecture, his work supports elements of the Artemis program including orbital habitats, surface transportation, and extra-vehicular activities. His work on mockups and prototypes is used to expand the understanding of humans in space through human-in-the-loop testing.*

Mark O. Cramer *joined NASA in 2017 at Johnson Space Center working for the Center for Design and Space Architecture (CDSA) under the Human Health and Performance contract. He has supported several programs at NASA including Gateway and Artemis and is currently the Lead Virtual Reality Developer for the CDSA.*



Jeffery M. Royer *is a software developer at Tietronix Software and works on the Lunar Terrain Vehicle project at the Johnson Space Center. He has 16 years of experience in software development, with many of those years supporting NASA. He earned his degree in Computer Information Systems from the University of Houston - Clear Lake. Outside his core profession, Jeffrey is a father of 2 active boys and a mentor for a First Robotics Competition (FRC) high school team.*