NASA/TM-20230014137

NASA's Center Innovation Fund (CIF) Internal Research and Development (IRAD) Handling Qualities Study on the Mikrolar Motion Platform Test Report

Harry "Chip" Litaker
NASA/Aerospace Corporation
Flight Systems Branch

Gordon Vos
NASA Johnson Space Center
AST, Crew Station Systems

Asher Liebermann
NASA Johnson Space Center
Simulation & Graphics Branch

Lee Bingham
NASA Johnson Space Center
Simulation & Graphics Branch

Mark Cramer
NASA/GeoControls
NASA Center for Design and Space Architecture

Terence Gelo
NASA/KBR
NASA Center for Design and Space Architecture

Nadia Scharunovych
NASA/KBR
NASA Center for Design and Space Architecture

Athena Frangoudis
NASA/JES Tech
NASA Center for Design and Space Architecture

Jeff Royer
NASA/METECS
Spacecraft Software Engineering

National Aeronautics and
Space Administration

Johnson Space Center
Houston, Texas 77058

September 2023

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ACRONYMS

"	inches
%	percent
<	less than
>	greater than
º	degree
1/6-g	Lunar Gravity
1-g	Earth Gravity
ABC	Artemis Base Camp
A/V	Audio/Video
AVO	Audio/Video Operator
CAHQRS	Cranfield Aircraft Handling Qualities Rating Scale
CF	Cranfield Road Vehicle Dynamic Qualities Rating Scale
CH	Cooper-Harper Handling Qualities Rating Scale
CIF	NASA’s Center Innovation Fund
cm	centimeters
CRVDQRS	Cranfield Road Vehicle Dynamic Qualities Rating Scale
D	Disorientation
deg	degree
DEM	Digital Environmental Model
DOF	Degrees of Freedom
EHP	NASA's Extravehicular Activity and Human Surface Mobility Program
EMS	Emergency Medical Service
EVA	Extravehicular Activity
FAM	Familiarization
g	gravity
GM	General Motors
GTU	Ground Test Unit
GUNNS	General-Use Nodal Network Solver software
HA	Hazard Analysis
HAB	Habitat
HC	Hand Controller

ACRONYMS

HITL	Human-In-The-Loop
HLS	Human Landing System
HQ	Handling Quality
Hzs	Hertz
ICC	Intra-class correlation coefficient
IQR	Interquartile Range
IRAD	NASA's Internal Research and Development
JEOD	Johnson Space Center’s Engineering Orbital Dynamics Model
JSC	Johnson Space Center
k	thousands
kg	kilograms
khp	kilometers per hour
km	kilometer
kW	kiloWatt
kW-h	kiloWatt-hour
lbs.	pounds
LED	Light Emitting Diode
LRO	Lunar Reconnaissance Orbiter
LRV	Lunar Roving Vehicle (Apollo)
LTV	Lunar Terrain Vehicle
M	Mean
m	meter
max	maximum
Mbdyn	MulitBody Dynamics (a NASA custom internal software package)
Mdn	Median
mhp	miles per hour
min	minimum
mins	minutes
mm	millimeter
MSFC	Marshall Space Flight Center
MT	Motion Table

ACRONYMS

N	Nausea
NASA	National Aeronautics and Space Administration
NASA-TLX	NASA's Task Load Index
O	Oculomotor Disturbance
ø	diameter
PR	Pressurized Rover
rad/s	Radians per second
RAF-IAM	United Kingdom's Royal Air Force Institute of Aviation Medicine
SA	SAE-J1441 Subjective Rating Scale for Vehicle Ride and Handling
SAE	Society of Automotive Engineers
SD	Standard Deviation
sec	second
SES	Systems Engineering Simulator
SESMT	Systems Engineering Simulator Motion Table
SESOP	Systems Engineering Simulator Operation Procedure
SESPCC	Systems Engineering Simulator Process Control Center
SMTD	SES Motion Table Director
SMTO	Simulation/Motion Table Operator
SPR	Small Pressurize Rover
SS	Simulator Sickness
SSQ	Simulator Sickness Questionnaire
TRR	Test Readiness Review
TS	Total Score
VR	Virtual Reality
VSM	Virtual Shadow Maps
XI	Johnson Space Center Astromaterials Research and Exploration Science Division
Yrs	Years

EXECUTIVE SUMMARY

In order to support the National Aeronautics and Space Administration's (NASA) Extravehicular Activity and Surface Mobility Program (EHP), system engineers, designers, and researchers embarked on a yearlong challenge to develop a new lunar rover-based motion table simulator to study handling qualities of lunar rovers in the lunar South Pole region, support development research for any lunar rover vendor, and provide a lunar training capability for future lunar/planetary astronauts. 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.

Funding from 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. This grant provided the opportunity to build a full motion table system architecture, scientifically accurate virtual lunar South Pole terrain and lighting environment and a human certified single seat with single hand controller rover cockpit. This report describes the work that was completed within a single year. The teams installed the motion table platform and associated hardware, enhanced and upgraded the visual environment to Unreal 5.2 improving simulation performance, completed two washout algorithm synchronizing sessions for table motion and visual environment, developed operations, emergency, training, and maintenance documentation, install a physical rover cockpit mockup, interface Virtual Reality (VR) headset with the overall motion system, received a human certification for the single cockpit. Testing simulated 1/6g loads and visuals with the motion table to examine if this was an effective simulation with operator in a 1g physical environment, and a preliminary lunar rover handling qualities study using the motion system architecture.

Testing involved thirteen test drivers over a period of 3 weeks at the Johnson Space Center (JSC) Systems Engineering Simulations (SES) Motion Table (MT) Facility. Test drivers accomplished two different driving courses: 1) a test track consisting of seven individual tasks and 2) a 5 kilometer (km) long traverse course where driver could experience a nominal lunar mission. Three different handling quality scales were used to understand if a correlation between scales existed. As a secondary objective researcher all collected data on the effects of simulator sickness with difference gravitational environments. Results indicated the Society of Automotive Engineers (SAE)-J1441 Subjective Rating Scale for Vehicle Ride and Handling exhibited a strong correlation with the Cooper-Harper Handling Quality Rating Scale and the Bedford Workload Rating Scale. This provides justification for the use of the SAE-J1441 as a handling quality method for lunar rovers. Test drivers preferred the short test track tasks over one long traverse task for handling qualities. Test track tasks were developed track standards from the automotive industry, military standards, off-road industry and the aerospace community. Tasks included 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, and up/cross/down slope tasks. Of the seven individual driving tasks, crater rim driving using the crab mode receive a failing SAE score. This is due the rocky terrain around the crater while using the crab steering mode. There

were a lot of inconsistencies with how the hand controller would correlate the inputs to the vehicle movement. Cruise control for maintaining speed and new controller mapping could alleviate the issue. A majority of the test track performance data concurred with what little historical Apollo Lunar Roving Vehicle (LRV) driving data from the lunar surface that was available (Table 1). Indicating, the simulation motion architecture model, though not perfect, is close by producing data that matches actual data. With the 5km long traverse, researchers received general knowledge of how a crewmember would feel after a complex traverse path noting the test drivers reported 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.

Table 1. *Apollo Lunar Roving Vehicle (LRV) Speeds versus NASA Lunar Terrain Vehicle (LTV) Speeds*

Rover Missions	Flat/Level/Straight Terrain Speed (kph)	Up Slope Speed (kph)	Down Slope Speed (kph)	Cross Slope Speed (kph)	Obstacle Avoidance Speed (kph)
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 Study	**11.7**	**5.5**	**5.7**	**5.7**	**4.2**
Apollo LRV sources: [45,46,47]					

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 1/6 gravity (g) 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, which took approximately 40 to 45 minutes, is where the majority of the simulator sickness occurred due to the bouncy rocky terrain and the constant weaving to avoid craters. Additionally, researchers confirm that simulator sickness is cumulative over time with some individuals getting worst symptoms while other adapted.

Future plans for the motion table system at Johnson Space Center (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).

1.0 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) Automation and Robotics Systems 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 is proposing 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 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. Furthermore, the VR software collects data for 532 parameters for evaluators to analyze vehicle performance as well as human performance in near real-time. The result of this study ensures a broadly applicable method of testing for unpressurized as well as pressurized rover designs.

2.0 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 expended 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.

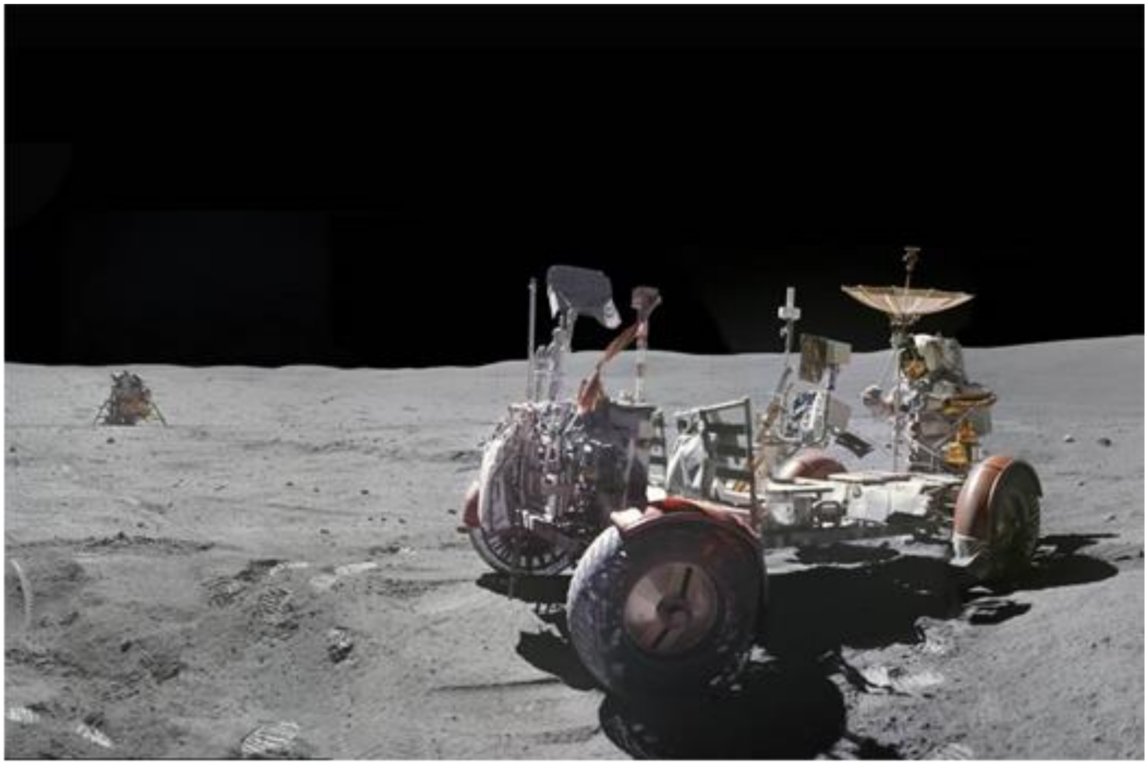


Figure 1. The Apollo Lunar Roving Vehicle (LRV). [Curiosity NASA]

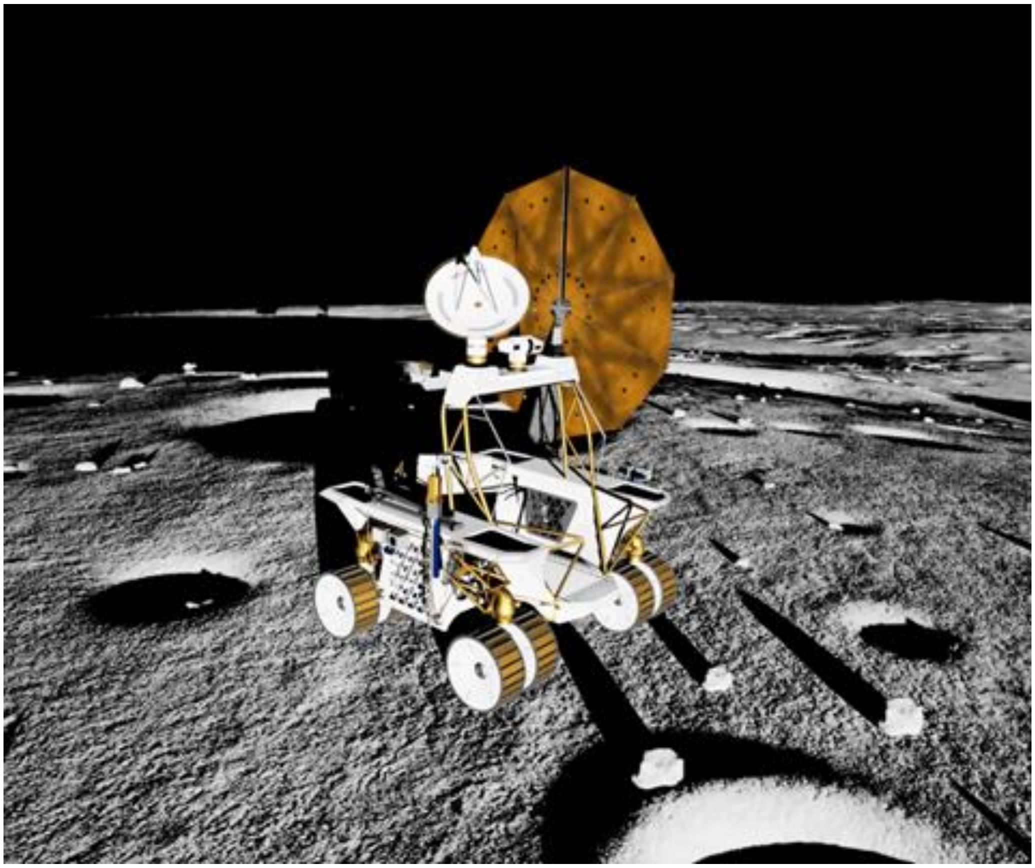


Figure 2. The Lunar Terrain Vehicle (LTV) in the option 4 configuration.

3.0 DEVELOPMENT OF THE MOTION TABLE

3.1 The Marsh Space Flight Center's LRV Simulator

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 int 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 5).

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

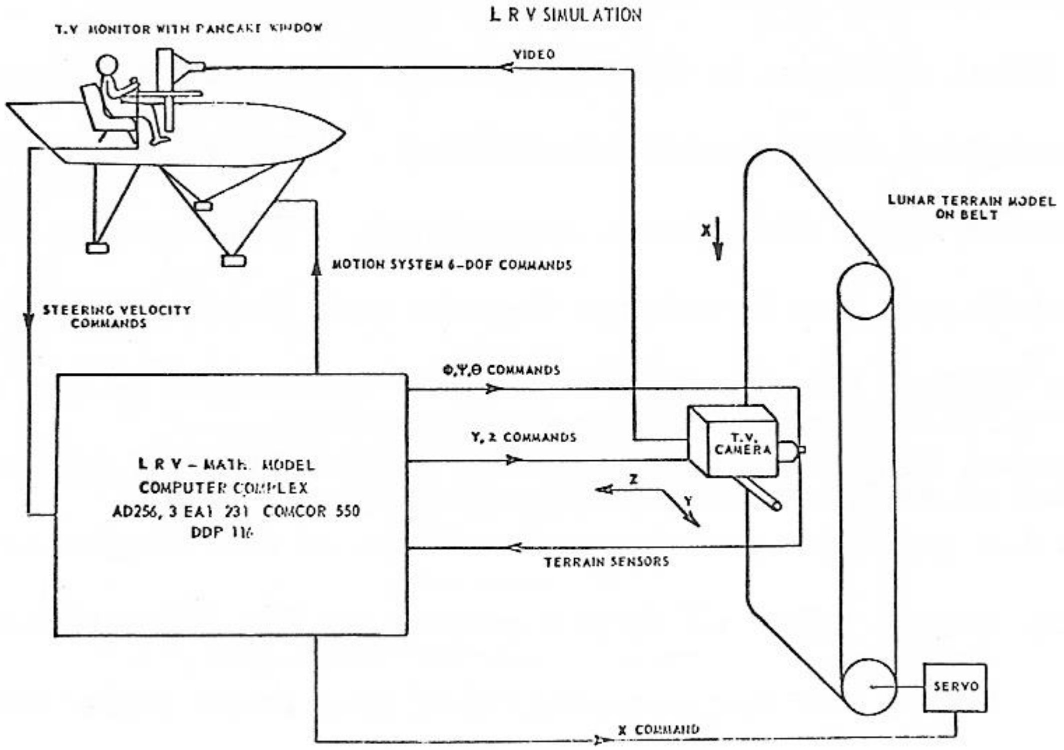


Figure 4. Operational diagram of the LRV simulator [5].

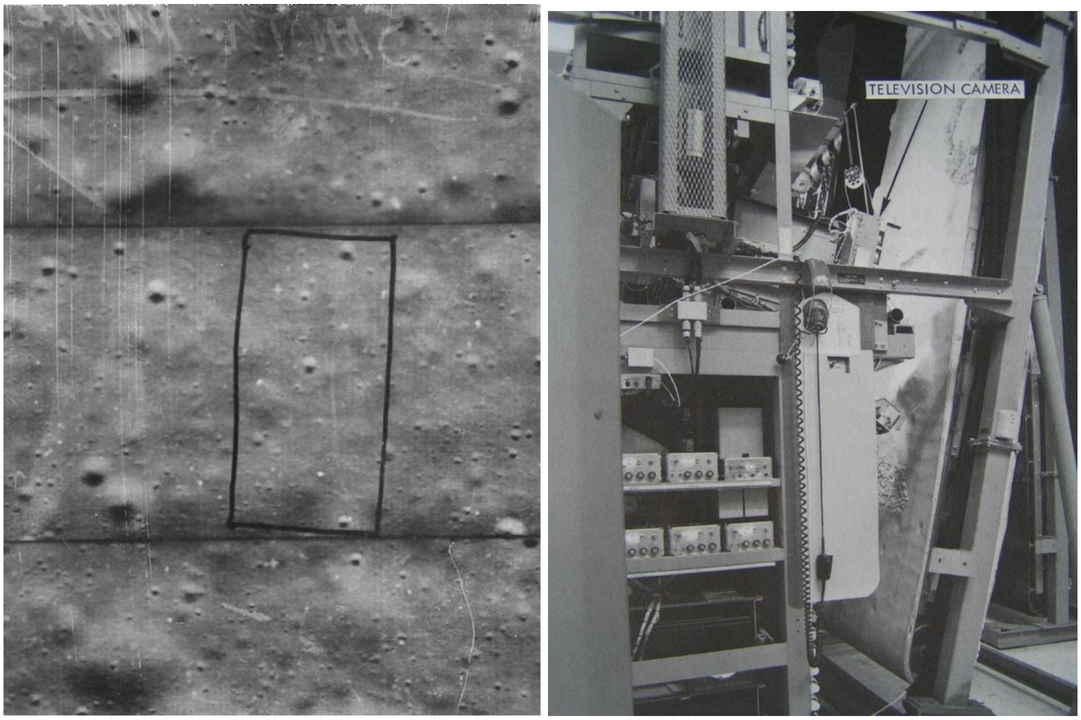


Figure 5. On the left the map of Maria area used in the LRV simulator. The black square is the area is seen by the test subject in the simulator. The right photo in the moving map and television camera [5].

3.2 Johnson Space Center's (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. This development of the motion platform originated as an Internal Research and Development (IRAD)-funded opportunity to explore the benefits of including real-time and realistic motion feedback in analog testing. The project provided a motion platform that responds to user input and environmental reactions in a virtual reality space. Phase one of the project allowed 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) 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. The maximum award in $100k for up to a maximum of 3 years. Every year must be recompleted. 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 the 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 fully developed, it will be available to assist potential rover vendors with design and test as requested. It will enable human factors engineering studies and will be an option for mission planning exercises and surface mobility training for future Artemis missions. Development of the facility is consistent with EHP's near term goals for Human Surface Mobility with Unpressurized and Pressurized Vehicles. In this report, the authors will discuss the first phase of development and then give the reader a glimpse into phase two and beyond.

3.3 The Mikrolar Motion Table

This development project started in October 2022. The Systems Engineering Simulator (SES) team had already purchased the Mikolar Motion Platform making facility modifications on the Mini Dome (Figure 6) located in Building 16 at Johnson Space Center (JSC). To house the unit which was sitting on a pallet (Figure 7) along with a proposed single race car seat (Figure 8). 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) (46 inches) in height with a total height range of 147.32 cm (58 inches) (Figure 9). Table 2 shows the operational specifications of the motion platform. In January 2023, with the motion platform in place and wired in the Mini Dome, Mikolar representatives came over to NASA to setup 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 Mikolar system at this time.

Figure 6. The Mini Dome facility being prepared in 2022.

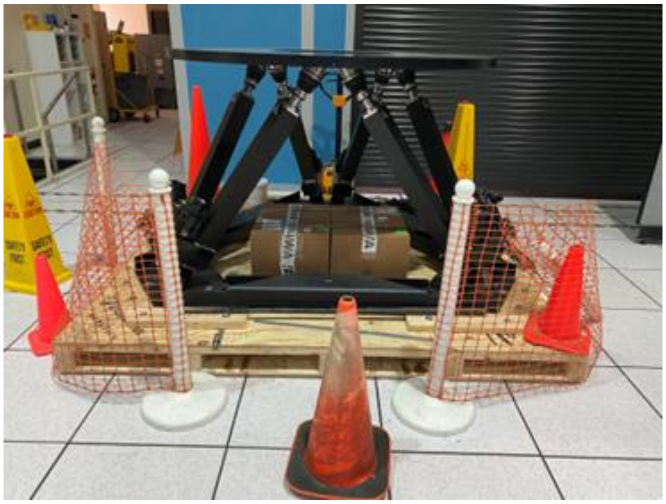


Figure 7. Mikrolar table on a pallet in January 2023.

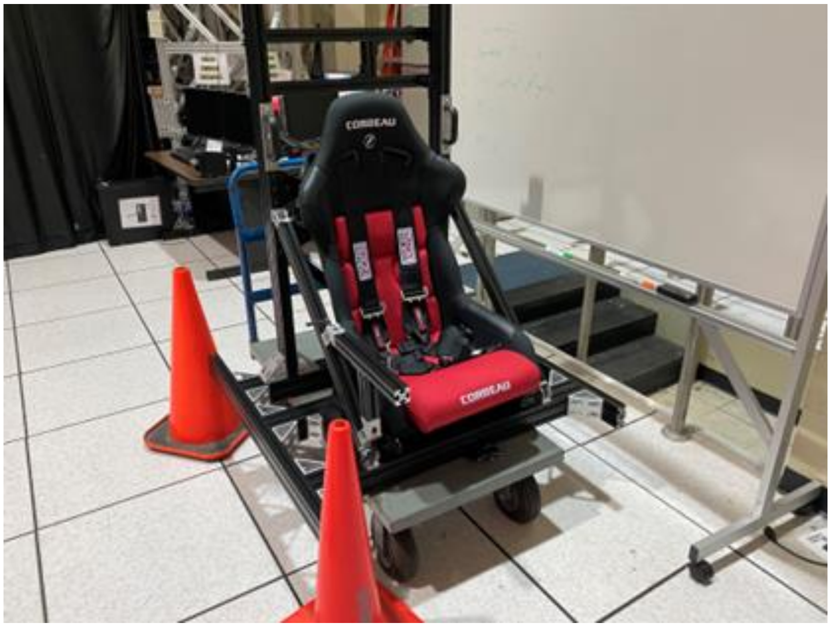


Figure 8. The race car seat of a frame in January 2023.

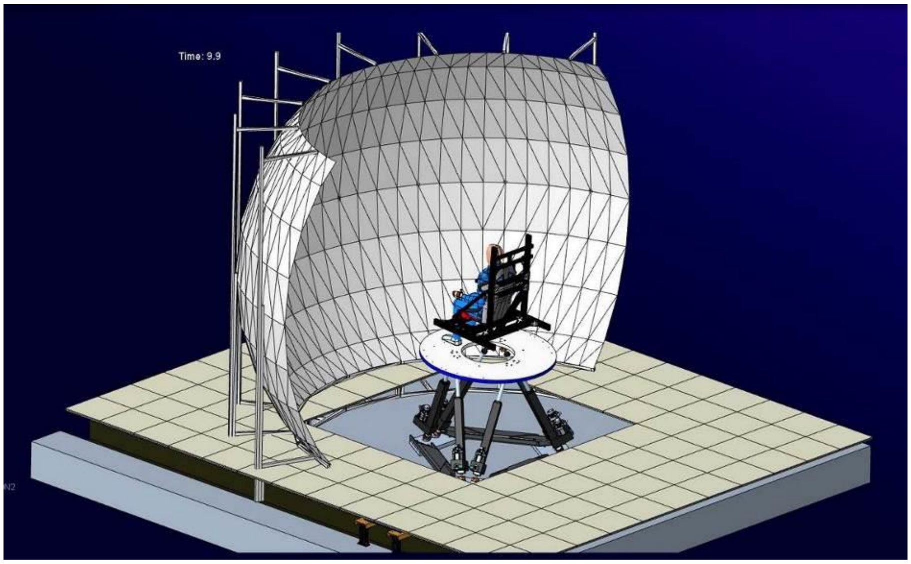


Figure 9. The B16 Mini Dome with motion platform.

Table 2. *Mikrolar Motion Platform Operational 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°

Table 2. *Mikrolar Motion Platform Operational Specifications*

SPECIFICATION	DATA
Repeatability	1 mm
Accuracy	1 mm
Mechanical Brakes	All Axes
Electric Motors	Six

3.4 Phase One Development of 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 simulation [50] framework. The original framework was developed in 2019 under the Digital Environmental Model (DEM) project for the lunar Human Lander System (HLS). The visual simulation was first used in a Human-in-the -loop (HITL) May 2022 with the test team examining the effects of lunar lighting on rover driving and ExtraVehicle Activity (EVA) events as the simulation team acquire NASA's Lunar Terrain Vehicle (LTV) front entry rover model as a reference design (Figure 10). The model already had employed a six degree-of-freedom physics-based rover suspension, propulsion and electric motor driven steering. 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) [51] model, a representative electrical power system model developed using General-Use Nodal Network Solver (GUNNS) software [52], 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 representative electrical power system model consists of solar array, solar array regulator, batteries, constant power load for rover hotel load, and motor-gearing modules for propulsion and steering. The dimensions of the simulated rover are illustrated in Figure 11. 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 kilometer per hour (kph) (7.46 miles per hour (mph)). Velocity requirements for the LTV is a maximum of 15 kph (9.32 mph). The LTV simulation capabilities are shown in Table 3. With lessons learned for the 2020 HITL, the simulation team decided to make a major jump for a custom inhouse simulation software development package to the Unreal 5.2 virtual reality software development package. The upgrade did enhance the visual rendering of the vehicle.

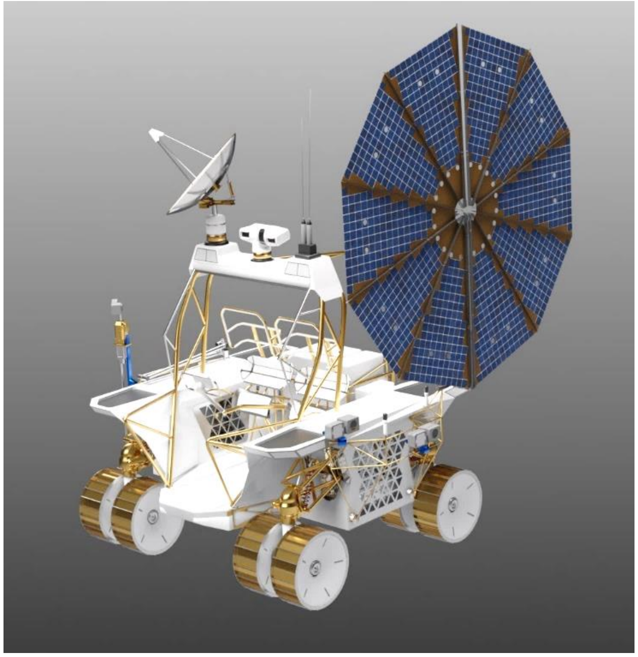
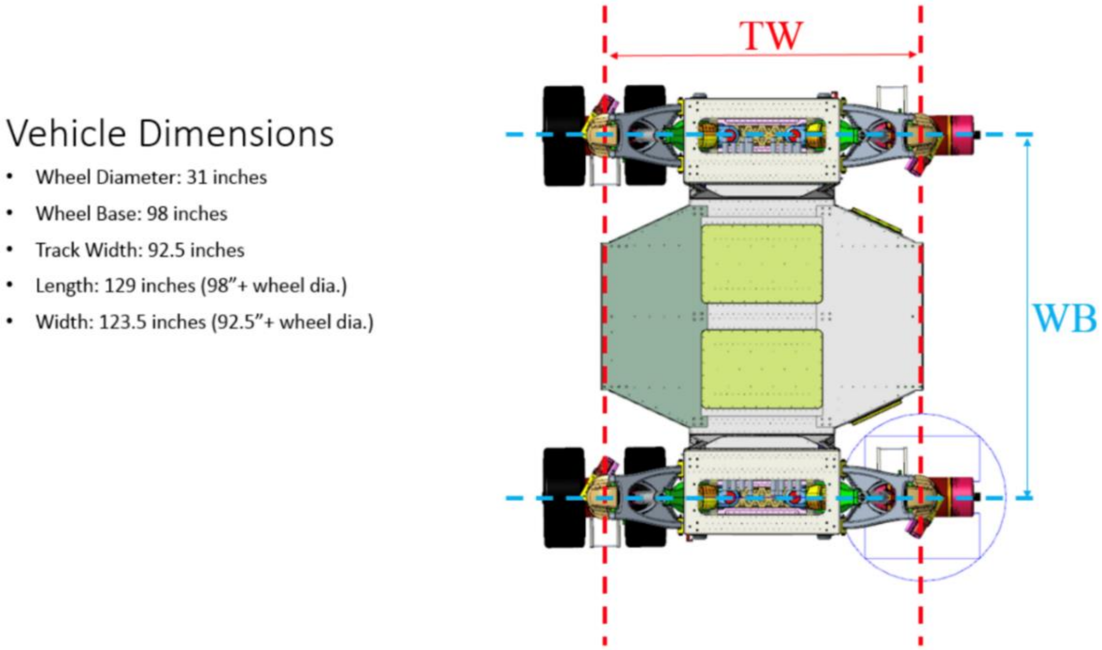


Figure 10. The virtual front entry LTV test vehicle.



Vehicle Dimensions

- Wheel Diameter: 31 inches
- Wheel Base: 98 inches
- Track Width: 92.5 inches
- Length: 129 inches (98"+ wheel dia.)
- Width: 123.5 inches (92.5"+ wheel dia.)

Figure 11. Dimensions of the simulated rover being used for testing.

Table 3. *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)

Table 3. *LTV Virtual Simulation Capabilities*

Min Slope Climb (uphill@800kg payload)	20	Degrees (deg)
Contact Model	Frame geometry and Pong contact with 4 wheels models	
Steering Modes	Ackermann 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.*		

With lessons learned for the 2022 HITL, the simulation team decided to make a major jump for a custom inhouse simulation software development package to the Unreal 5.2 virtual reality software development package. The upgrade did enhance the LTV performance; however, due to the model motor controllers and the new virtual engine (Unreal 5.2) the max speed of the vehicle implemented in the simulation is 12 kph (7.46 mph) instead of required 15 kph (9.32 mph). The added speed parameter caused some performance issues with the virtual simulation. A solution to this performance issue for future testing is being worked by the SES facility. The virtual rover has full body dynamic modeling and is required to handle slopes of +/- 20º (up-, down-, cross-slope) per the actual LTV performance requirements. In addition, the virtual vehicle has a full lighting and camera array (Figure 12 and Figure 13).

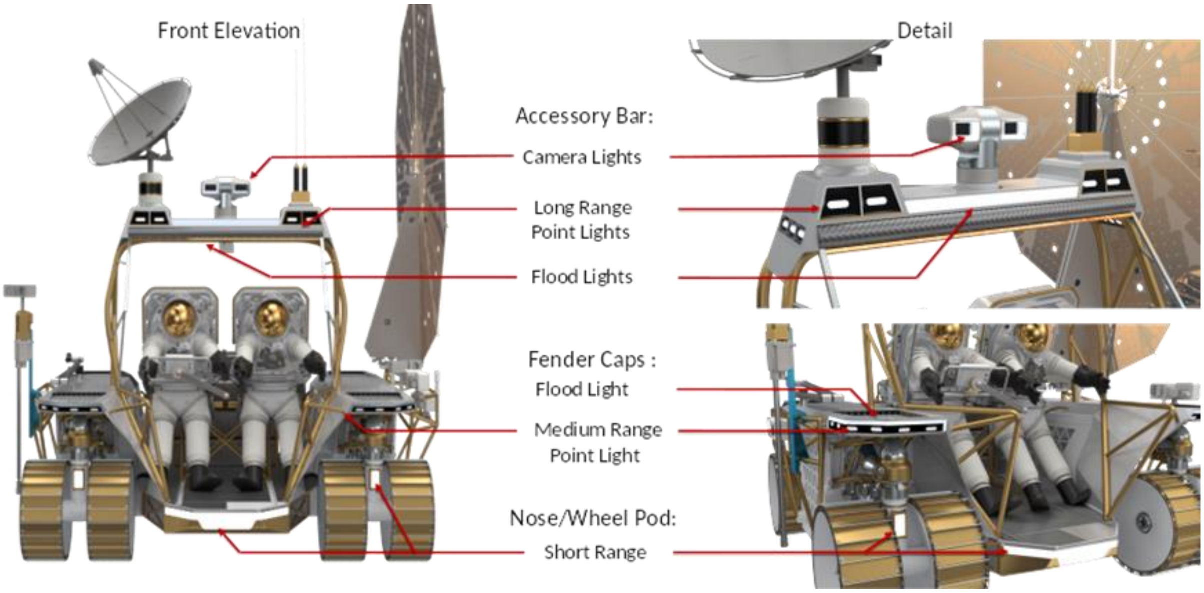


Figure 12. The LTV camera and lighting positions.

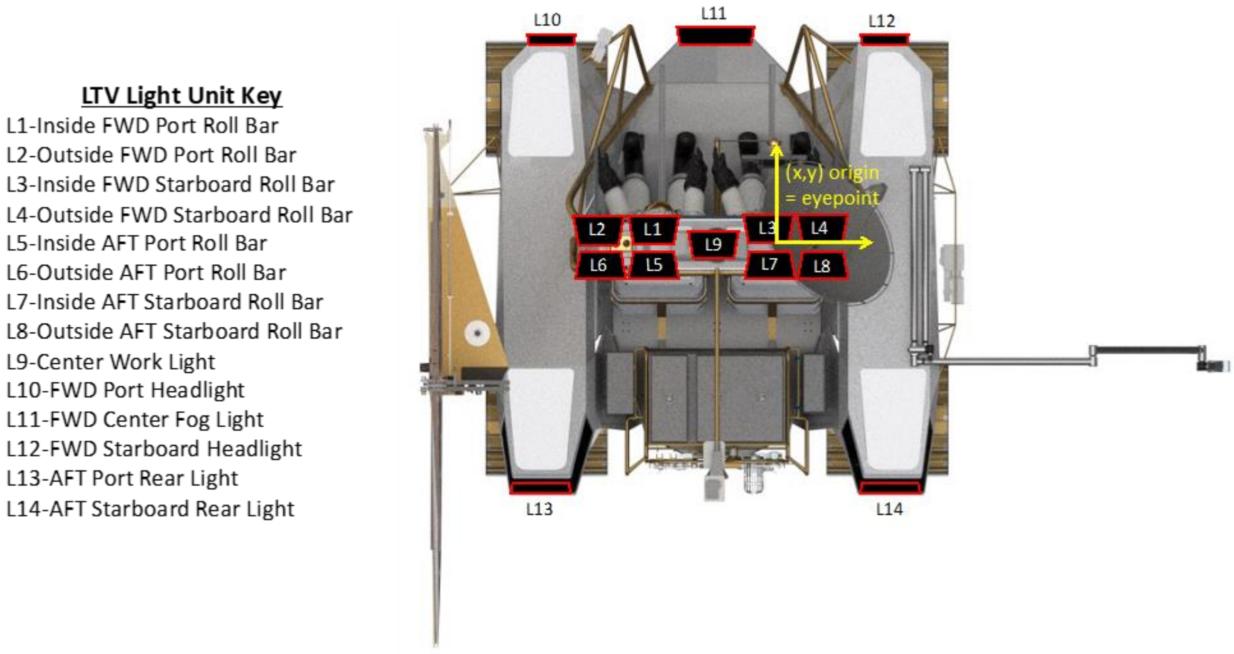


Figure 13. The LTV lighting unit locations.

The rover's terra-mechanics model for wheel to soil (regolith) interaction which resembles the lunar surface more closely (Figure 14). Early modeling used regolith parameter values from studying the sample collection from the Apollo missions (Figure 15) [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. However, the model cannot simulate the situation where a wheel digs into loose soil when rotating.

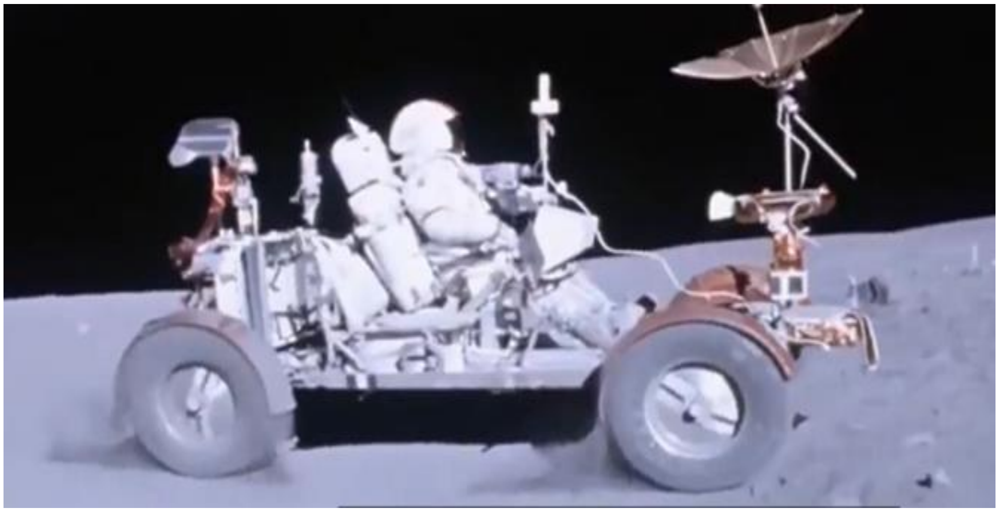
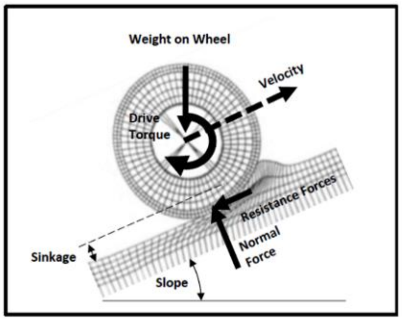


Figure 14. The LRV driving over the lunar surface. Note the wheels digging at the lunar soil. [Photo Curiosity NASA]



Modeling Soil Reaction as a Nonlinear Spring

$$P = \frac{W}{A} = kz^n$$

$$k = \frac{k_c}{b} + k_\phi$$

$$\text{Therefore: } \frac{W}{A} = \left(\frac{k_c}{b} + k_\phi\right) z^n$$

W = normal force on the wheel
A = contact surface
z = soil sinkage
n = exponent of sinkage
b = wheel width
k_c = modulus of cohesion
K_ϕ = modulus of friction

Figure 15. A diagram of a rover wheel and soil resistance along with the soil reaction formula.

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 meter (m) (1,640 feet) radius landing area and a notional 500-m (1,640 feet) radius habitat area (Figure 16) approximately 17 km (10.56 miles) from the lunar south pole, as well as a 500-m (1,640 feet) radius area inside the Bear Paw (Figure 17), approximately 8.9 km (5.53 miles) west from the landing site (Figure 18). Terrain data is based on 5m/pixel DEM data and 5m/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 small set of rocks was also provided based on these crater locations to give the effect of increased rock distribution around some of the larger craters. A 500-m (1,640 feet) wide corridor between the landing site and Bear paw area was populated to the same level of fidelity using the same techniques. Here, the 500-m (1,640 feet) wide corridor can be observed based on the crater distribution in the simulated image. 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. Appendix A gives more detail on the terrain elements that are in the simulation.

Figure 16. Screen capture of Artemis Base Camp terrain (notional surface habitat on the right).

Figure 17. Screen capture of Bear Paw terrain.

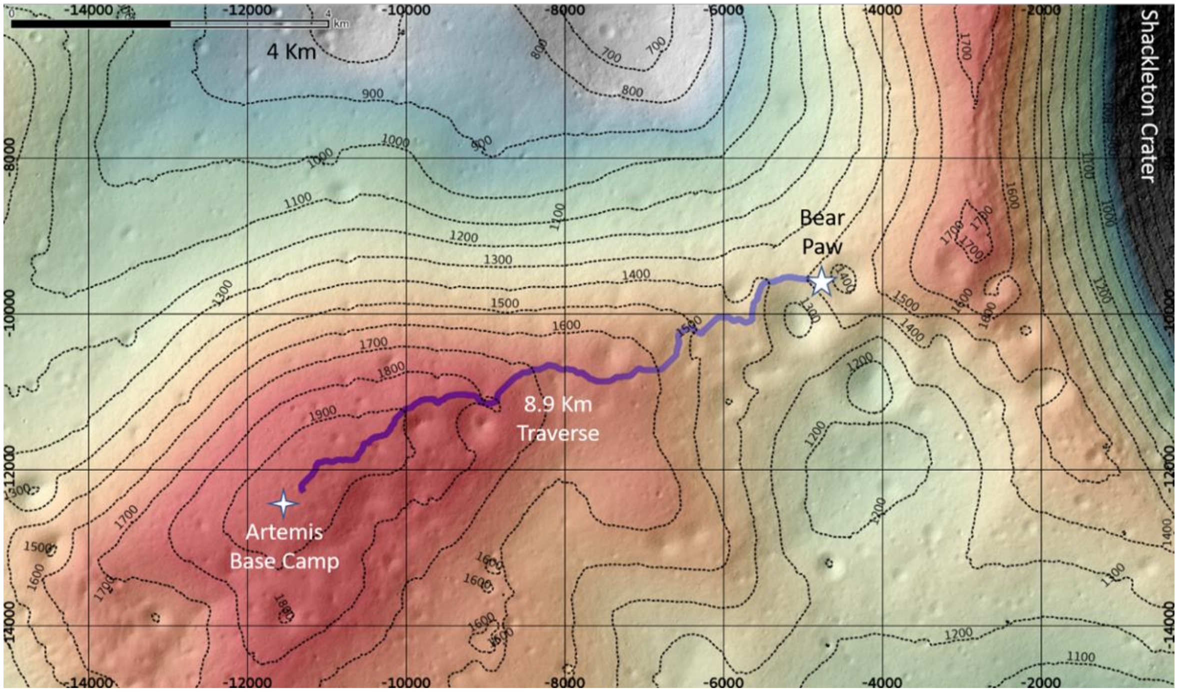


Figure 18. Top-down view of the simulated terrain, noting the Artemis Base Camp and Bear Paw areas with an 8.9 km (5.53 mile) corridor between them.

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 19). 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 19. The simulated South Pole Lunar environment.

3.5 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. Now the team had developed a full motion platform architecture (Figure 20) 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 Simulator Motion Table (SESMT) console computer. The SESMT Operator Console System which control the table motion, simulation host computer an also receives user input command. 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 Clear Com wireless communication intercom system for the entire team (Table Director, Table Operator, A/V Operator, Test Conductor/Customer) and test subject. Finally, the Single Seat Mockup Rover Cockpit with an adjustable seat and 5-point harness, a generation 3 Space Exploration Vehicle (SEV) joystick hand controller, safety railing and a slip resistant deck. An adjustable footrest was added right before the IRAD testing began.

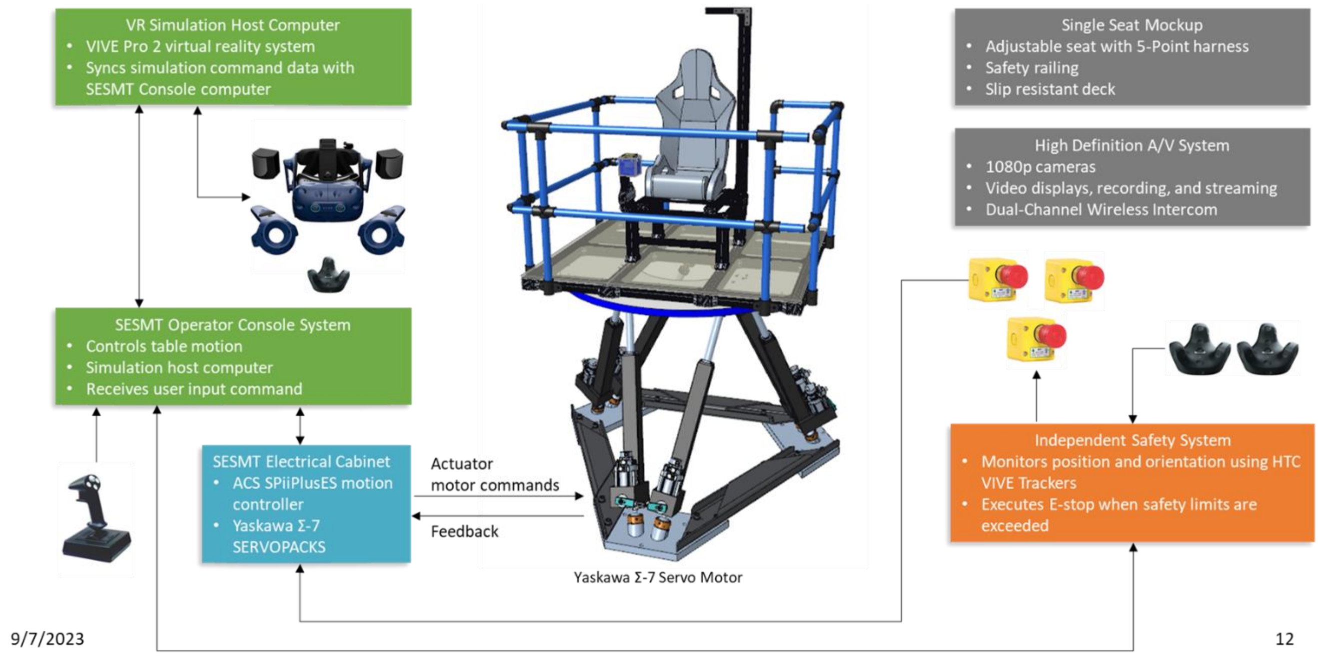


Figure 20. The SES Motion Table (SESMT) Architecture.

3.6 Motion Table Documentation

With testing and data analysis on the performance of motion table and vibration data of the seat for humans, the team started developing all types of protocols that the facility will need to conduct business safely. A complete Hazard Analysis (HA) was developed illustrating the possible hazards that could be encounter with the facility with safety controls to migrate those hazards. Another small team started developing all the Operations and Emergency Procedural documents. Two documents and a database were developed, written, and approved: 1) the SES Motion Table Maintenance Procedures (SESOP 2246), 2) the Detailed SES Motion Table (SESMT) Operation Procedure (SESOP 2248), and 3) the SES Process Control Center (SESPCC) database where all the documents live and are available online. All the operating procedures are used to perform the functions of operating and maintaining the motion table by SES personnel certified in one or more of the following roles: 1) SES Motion Table Director (SMTD); 2) Simulation/Motion Table Operator (SMTO); and 3) Audio/Visual Operator (AVO). The SESMT emergency response procedures were developed with input for the JSC occupational health, security, Emergency Medical Service (EMS), fire, and space operations personnel. The emergency procedures are included in SESOP 2248 as follows: 1) Medical Emergency Response, 2) Fire Emergency Response, 3) Equipment Failure Emergency Response, 4) Power Failure Emergency Response, and 5) Emergency Contact Numbers. A training document also had to be developed to train all SES personnel who would support motion table operations. This document is the SES Motion Table Operations Training & Certification document (SESOP 2249). The facility and personnel also had to conduct both medical and hardware emergency drills. All of this work was in preparation for a Test Readiness Review (TRR) to approve of the facility, the motion table hardware, the motion table software, the visual simulation software, and the systems architecture in order to have the facility certified for human testing.

3.7 Motion Table Human Certification And Benefits

The team received their human rating certification on 31 March 2023. With the certification in hand over the next two months, the motion table teams refine 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 21).

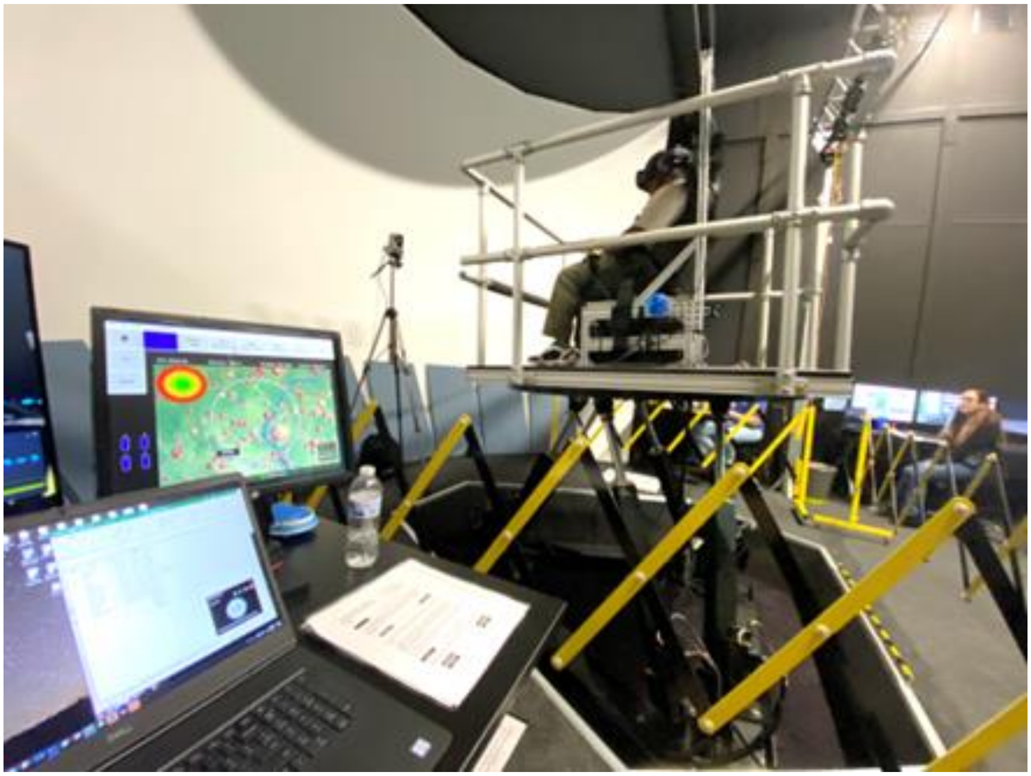


Figure 21. The finished Mikrolar motion platform located in the SES Mini Dome.

The benefits of such a facility on the testing environment are far-reaching. Currently, with Phase one development, the motion platform is configured for use with a single shirt-sleeve test subject in a single seat with a single hand controller under a VR headset. The goal of the initial design is to anticipate future potential and to strategically redesign the platform so that it can accommodated more complex vehicle cockpits for future testing. In the near future, there are potential benefits for ongoing projects in NASA's EHP program, if the capabilities of the motion platform are extended beyond this grant. By adding the possibility of a two-seat rover cockpit and the possibility of pressurized suit testing while onboard the motion platform, the team can facilitate potential near-future use by EHP commercial vendors.

4.0 MOTION TABLE HANDLING QUALITIES STUDY OBJECTIVES AND PRODUCTS

There are two objectives for this study that the team investigated to advance the general knowledge of using a motion platform. Each objective will be tested using two different hand controller designs, driving a specific test task course and an overall long duration course while on a motion platform. The objectives of interest are:

- 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.

5.0 TESTING HARDWARE USED WITH THE MOTION TABLE

Hand controllers are the heart on any vehicle that is being operated by a human. Early testing of the LRV hand controller used a Boeing style vertical pistol grip controller in a LRV simulator (Figure 22). The LRV simulator was an SMK23 air force flight simulator modified where on the original moving platform a replica of the LRV driving displays and controls were incorporated [5]. Though little is known of how this pistol grip controller worked, an assumption of the functional mapping would have been the same as the later T-Handle design providing Ackermann functionality such as steering, acceleration, left/right turning, and braking commands Table 4. Rationale for this assumption is when the newly design T-Handle controller was tested by two astronauts for two hours each in the LRV simulator, approval of the design change was accomplished that day. This could mean that the vertical pistol and the T-Handle had the same mapping setup with only a grip change.

Figure 22. The Apollo LRV T-Handle controller and center display console. [Curiosity NASA]

Table 4. *LRV T-Handle Grip Controller Functional Mapping*

	Controller Direction	Element Motion	Function
LRV T-Handle Grip Controller	Forward	Push Controller Forward	Vehicle accelerates forward at 28º deflection
	Neutral	Push Controller Forward	Neutral on the Traction Drive at between Forward and Reverse deflection ~14º
	Backward	Push Controller Back	Brake at 14º forward of back deflection
	Lean Right	Push/Lean Controller to the Right	Rotate (Turn) Vehicle to the Right starts at 9º to 14º of deflection
	Lean Left	Push/Lean Controller to the Left	Rotate (Turn) Vehicle to the Left starts at 9º to 14º of deflection
	Thumb Switch	Puts Vehicle in Reverse	Vehicle accelerates in reverse when controller is moved 14º forward to the neutral position
	Engage Park Brake	Move Controller Fully Rearward	Engages the park brake
	Release Park Brake	Move Controller to a steer left position	Releases the park brake

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 Small Pressurized Rover (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 23). Rationale for this type of joystick was with the extra degree of freedom in the yaw direction it gave engineers a way to incorporate the crabbing function without relying on display software. Figure 24 and Table 5 illustrates the dimensions for the SPR joystick controller used for testing. The functional mapping of the SPR controller is illustrated in Table 6 and Figure 25. All units of measures are in centimeters and inches.

Figure 23. The CH Product MV4 Joystick in the SPR Generation 1B cockpit during field testing in 2009.

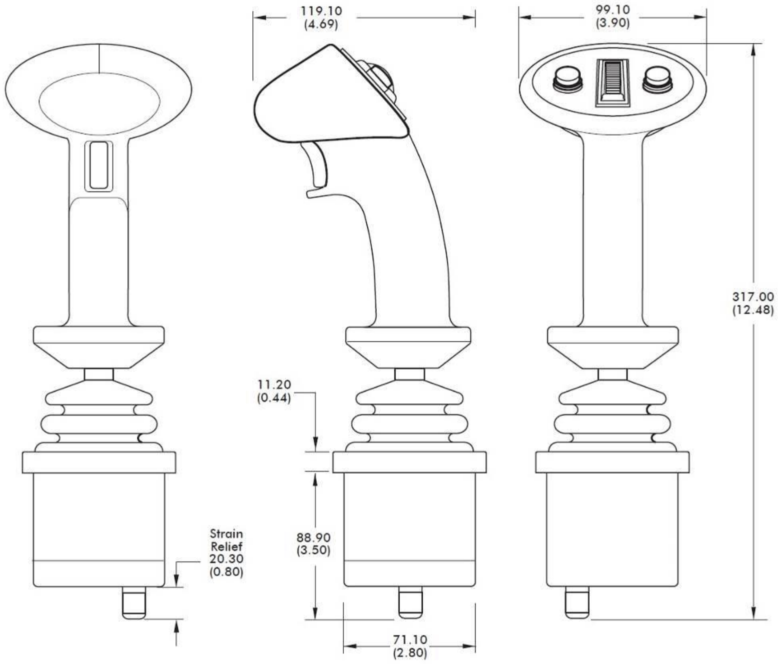


Figure 24. Dimensions of the SPR Joystick Controller used for testing. Units in millimeters (mm) (inches) [10].

Table 5. *The SPR Joystick Dimensions*

Element	Dimension (cm)	Dimension (inches)
Controller Length	11.9	4.69
Controller Height	31.7	12.48
Head Width	9.9	3.90
Grip Height	9.5	3.75
Grip Width	11.43	4.5

Figure 25. The SPR joystick.

Table 6. *The SPR Joystick Functional Mapping*

	Controller Direction	Element Motion	Function
SPR Joystick Controller	Forward	Push Controller Forward	Vehicle will move forward While in Cruse Control bumping stick forward quickly will add 0.5 kph to speed
	Backward	Push Controller Back	Vehicle will move backward While in Cruse Control bumping stick backward quickly will subtract 0.5 kph to speed
	Lean Right	Push/Lean Controller to the Right	Vehicle goes sideways to the right (wheels at 90°)
	Lean Left	Push/Lean Controller to the Left	Vehicle goes sideways to the left (wheels at 90°)
	Twist Right	Yaw/Twist Controller to the Right	Turns vehicle to the right. Can rotate/pivot on vehicle Z-axis
	Twist Left	Yaw/Twist Controller to the Right	Turns vehicle to the left. Can rotate/pivot on vehicle Z-axis
	Silver Switch	Cruise Control and Steering Mode	UP- Cruise Control (On/Off) DOWN-Steering Mode Ackermann Crab Mode
	White Button	White Button on lower left of Controller Head	Park Brake
	Castle Switch	Castle Switch center of Controller Head	Camera Lens Control: UP- Zoom In DOWN- Zoom Out
	Center Black Top Hat Button	Top Hat Button center left side on Controller Head	Camera Control: UP- Tilt Camera Down RIGHT- Pan Camera Right LEFT- Pan Camera Left DOWN- Tilt Camera Up
	Red Trigger	Red Trigger center of grip below Controller Head	Momentary Break (Not Shown in Figure)

6.0 STUDY DESIGN

Some definitions are needed to understand what the details of hand controller handling quality performance.

- Ability is the skill required of the operator to perform the action with the hand controller.
- Maneuverability is the actual physical motion of the operator's hand/wrist on the controller.
- Responsiveness is how the controller reacts to the operator's inputs.

Testing utilized thirteen engineering subjects of various backgrounds, in a shirtsleeve environment using a single-set LTV cockpit on a motion platform in the Systems Engineering Simulator (SES) mini dome location at Johnson Space Center's (JSC) Building 16 (Figure 26). The test driver population accomplished a task then rate that task using all three handling qualities scales. Handling quality scales will be randomized for each task, each overarching scenario and each subject. One concept hand controller was tested using two test courses: 1) a Test Track consisting of seven individual driving tasks and 2) a Long Traverse course gave the operator some experience in what a nominal lunar South Pole rover mission would be like driving from a Lander site to a habitat site (Table 7).

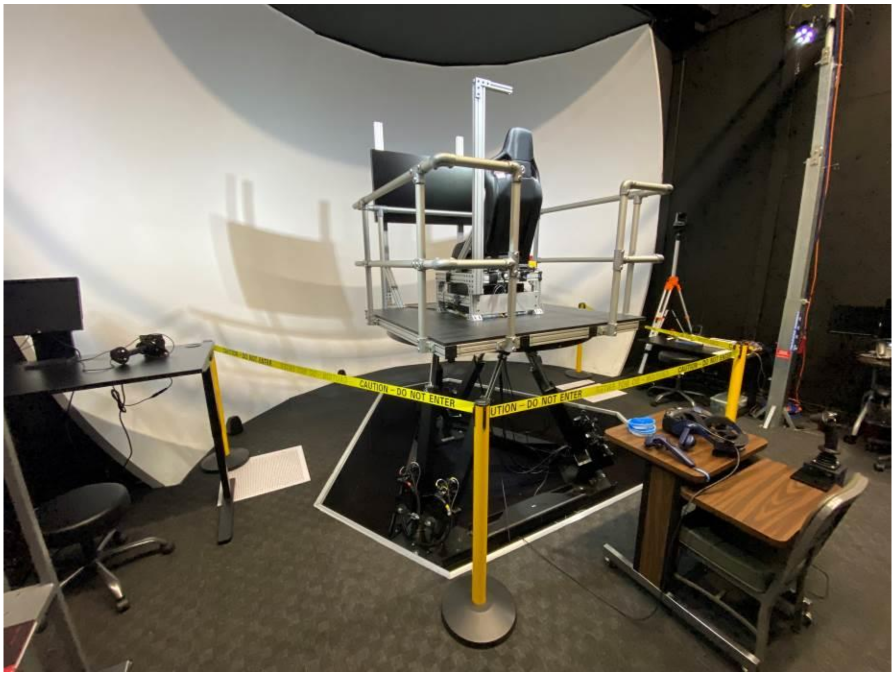


Figure 26. The motion platform in the SES Mini Dome facility.

Table 7. *Handling Quality Scale Test Matrix*

Subject	Course	Task	HQ[1] Scale 1	HQ Scale 2	HQ Scale 3
1	1	1	CF[2]	SA[2]	CH[2]
1	1	2	SA	CH	CF
1	1	3	CH	CF	SA
1	1	4	SA	CF	CH
1	1	5	CF	CH	SA
1	1	6	CH	SA	CF
1	1	7	SA	CF	CH
1	2	1	CF	CH	SA
2	1	1	CH	SA	CF
2	1	2	CF	CH	SA
2	1	3	SA	CF	CH
2	1	4	CH	CF	SA
2	1	5	SA	CH	CF
2	1	6	CF	SA	CH
2	1	7	SA	CH	CF
2	2	1	CH	SA	CF
3	1	1	CF	SA	CH
3	1	2	SA	CH	CF
3	1	3	CH	CF	SA
3	1	4	SA	CF	CH
3	1	5	CF	CH	SA
3	1	6	CH	SA	CF
3	1	7	SA	CF	CH

Table 7. *Handling Quality Scale Test Matrix*

Subject	Course	Task	HQ[1] Scale 1	HQ Scale 2	HQ Scale 3
3	2	1	CF	CH	SA
4	1	1	CH	SA	CF
4	1	2	CF	CH	SA
4	1	3	SA	CF	CH
4	1	4	CH	CF	SA
4	1	5	SA	CH	CF
4	1	6	CF	SA	CH
4	1	7	SA	CH	CF
4	2	1	CH	SA	CF
5	1	1	CF	SA	CH
5	1	2	SA	CH	CF
5	1	3	CH	CF	SA
5	1	4	SA	CF	CH
5	1	5	CF	CH	SA
5	1	6	CH	SA	CF
5	1	7	SA	CF	CH
5	2	1	CF	CH	SA
6	1	1	CH	SA	CF
6	1	2	CF	CH	SA
6	1	3	SA	CF	CH
6	1	4	CH	CF	SA
6	1	5	SA	CH	CF
6	1	6	CF	SA	CH
6	1	7	SA	CH	CF
6	2	1	CH	SA	CF
7	1	1	CF	SA	CH
7	1	2	SA	CH	CF
7	1	3	CH	CF	SA
7	1	4	SA	CF	CH
7	1	5	CF	CH	SA
7	1	6	CH	SA	CF
7	1	7	SA	CF	CH
7	2	1	CF	CH	SA
8	1	1	CH	SA	CF
8	1	2	CF	CH	SA
8	1	3	SA	CF	CH
8	1	4	CH	CF	SA
8	1	5	SA	CH	CF
8	1	6	CF	SA	CH
8	1	7	SA	CH	CF
8	2	1	CH	SA	CF
9	1	1	CF	SA	CH
9	1	2	SA	CH	CF
9	1	3	CH	CF	SA
9	1	4	SA	CF	CH
9	1	5	CF	CH	SA
9	1	6	CH	SA	CF
9	1	7	SA	CF	CH
9	2	1	CF	CH	SA
10	1	1	CH	SA	CF
10	1	2	CF	CH	SA

Table 7. *Handling Quality Scale Test Matrix*

Subject	**Course**	**Task**	**HQ[1] Scale 1**	**HQ Scale 2**	**HQ Scale 3**
10	1	3	SA	CF	CH
10	1	4	CH	CF	SA
10	1	5	SA	CH	CF
10	1	6	CF	SA	CH
10	1	7	SA	CH	CF
10	2	1	CH	SA	CF
11	1	1	CF	SA	CH
11	1	2	SA	CH	CF
11	1	3	CH	CF	SA
11	1	4	SA	CF	CH
11	1	5	CF	CH	SA
11	1	6	CH	SA	CF
11	1	7	SA	CF	CH
11	2	1	CF	CH	SA
12	1	1	CH	SA	CF
12	1	2	CF	CH	SA
12	1	3	SA	CF	CH
12	1	4	CH	CF	SA
12	1	5	SA	CH	CF
12	1	6	CF	SA	CH
12	1	7	SA	CH	CF
12	2	1	CH	SA	CF

[1] HQ = Handling Qualities

Scale Key:
[2] CF = Cranfield Road Vehicle Dynamic Qualities Rating Scale
[2] SA =NASA-SAE-J1441-23 Subjective Rating Scale
[2] CH = Cooper Harper Handling Quality Rating Scale

Testing started with the test conductor briefing the test driver on all the components they would be interfacing with during the test session and the handling quality rating scale they used. Testing consisted of a shirtsleeve driver entering the mini dome, receiving a facility brief and climbing onto the motion platform sitting in the seat and getting restrained. The test team assisted the test driver in getting arm rests, hand controllers, and a VR headset in the preferred, most comfortable position. 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 and again at the end of testing. This aided the test team in understanding how the simulation is affecting the subject at certain times during testing. If at any time the test driver feels "off" then testing was halted, and time given to the 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 (Table 8 and Table 9). After the task is completed, the test drive was asked to rate the handling qualities of the controller for that task using all three handling qualities in a random order and provide any comments for each scale. Then the test driver was teleported to the next task site. This continued until all seven individual test track tasks are 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. Much like an automobile manufacturer or the military would do for a new vehicle. Track parameters were taken for the automotive community, the military vehicle testing standards and the aerospace community [11, 12, 13, 14, 15, 16, 17]. Appendix B has the detail parameters of each test track task. These test track tasks will take approximately 45 minutes to complete. This tested the responsiveness and maneuverability of the vehicle along with the driver's ability to drive the vehicle using the controller(s) driving capabilities (e.g., moving the vehicle forward, reverse, turning, crabbing, acceleration, braking, etc.).

Table 8. *Handling Quality Test Elements with Proposed Timing*

Test Element	Tasks	Time (mins) per HC
Pre-Brief	Objectives	20
FAM	Getting use to HC and motion platform	15
Test Track Course	SSQ	0.5
	Straight Flat/Braking (2x speed)	10
	HQ Ratings/Workload	1
	Crater Field	4
	HQ Ratings/Workload	1
	Crater Rim	7
	HQ Ratings/Workload	1
	Inspection/Constant Turn	5
	SSQ	0.5
	HQ Ratings/Workload	1
	Down Slope	4
	HQ Ratings/Workload	1
	Cross Slope	4
	HQ Ratings/Workload	1
	Up Slope	4
	HQ Ratings/Workload	1
	SSQ	0.5
Break	Subject Break	10
Long Traverse Course	SSQ	0.5
	Nominal Lunar Mission	20
	SSQ	0.5
	Nominal Lunar Mission	20
	SSQ	0.5
	HQ Ratings/Workload	5
FAM = Familiarization		
HC = Hand Controller		
HQ = Handling Quality Scale		
SSQ = Simulator Sickness Questionnaire		

Table 9. *Total Test Timing on the Motion Platform*

Test Elements	Time (mins)
Test Track	46.5
Long Traverse	46.5
Pre-Test	35
Test Time Total	128

After a 10-minute break, the test driver was reseated on the test apparatus and made as comfortable as possible. The test conductor placed the test driver at the pre-determined HAB site. The driver was told their objective is to traverse the 5.0-kilometer (km) (3.12 miles) distance (Figure 27) 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. Subjects 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 to 60 minutes to complete. As the traverse planners only had LRO imagery to go by while developing the traverse, text drivers were told they could encounter some areas along the path that could not be traversed safely. If this occurred, the driver was allowed to deviate from the original traverse path for safer passage across the area; however, they had to rejoin the original path as soon as it was feasible. 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 (e.g., moving the vehicle forward, reverse, turning, crabbing, acceleration, braking, etc.) while avoiding terrain features, which assisted in the evaluation of the controller(s) handling quality responsiveness to the subject's inputs. After the completion of the long traverse, test drivers were given a handling quality using all three scales and acceptability questionnaires on the controller(s).

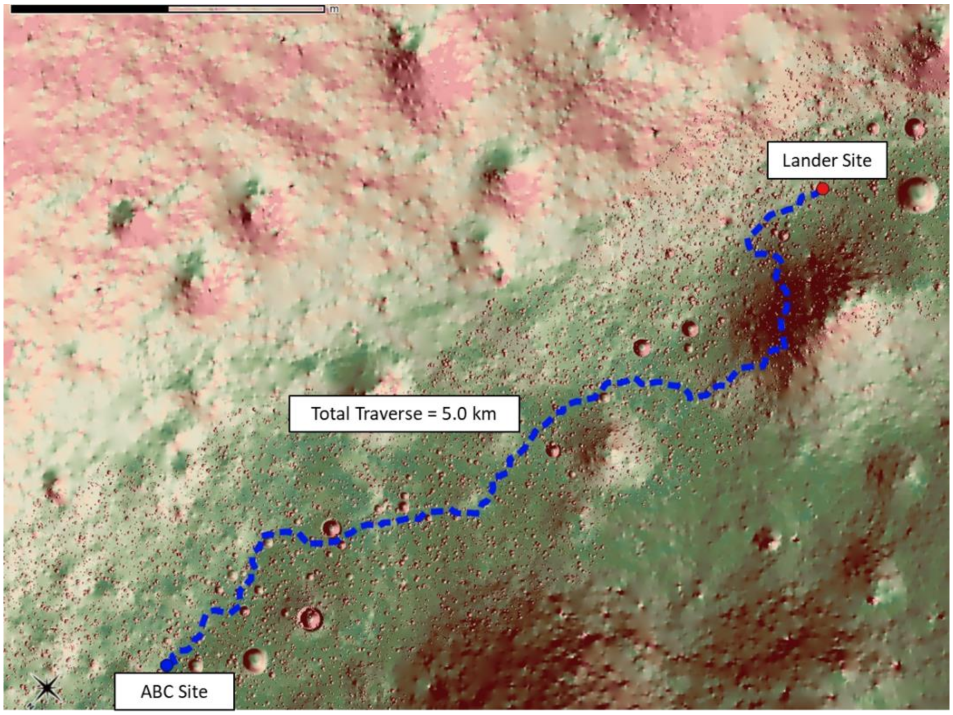


Figure 27. The 5.0 km (3.12 mile) long traverse course.

6.1 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 10 is the objective data which was required.

Table 10. *Remote Operation Objective Data Collection*

Data	Units
Total Task Time	seconds
Average Velocity	kph
Distance Traveled	km
Slope/Elevation	Degrees (º)
Rock Contact	Frequency Number
Cruise Control	On/Off
Seat Vibration	Hzs
Rock Contacts	Frequency of contacts
Breadcrumb Trail	Δ between distance from original traverse
Hand Controller Inputs	
Extent	Numerical value
Duration	seconds
Delay	1/10th of a second
Toque	Newtons per axis

As for subjective measures, the simulation quality rating scale, the Acceptability Rating Scale, the NASA-SAE-J1441-23 Subjective Rating Scale for Vehicle Ride and Handling, the Cranfield Road Vehicle Dynamic Qualities Rating Scale (CRVDQRS), the Bedford Workload Scale, and the Kennedy Motion Sickness Scale (SSQ) were used. The post-test questionnaire portion of the test used the Acceptability Scale.

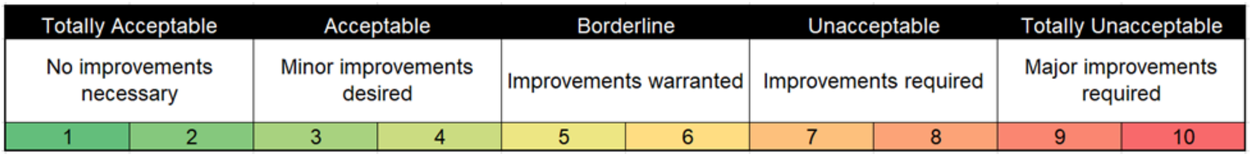
6.1.1 The Acceptability Scale

Acceptability ratings were collected for different aspects of the hand controller functions and test test driver interactions with the hand controller. Specific comments on desired/warranted/required improvement and/or minor/moderate/unacceptable deficiencies will be noted for any acceptability rating of 3 or higher. The acceptability ratings were collected via an electronic questionnaire administered on a laptop. The questions included, but are not limited to, the acceptability of the following:

- The reach to the hand controller
- The physical characteristics of the hand controller
- The functional mapping is easy to understand
- The ability to accelerate and maintain speed
- The ability to brake and come to a compete stop
- The ability to drive forward
- The ability to drive in reverse
- The ability to turn left or right
- The ability to crab
- The ability to drive up a slope
- The ability to drive down a slope
- The ability to drive cross slope
- Ease of maneuverability to avoid rocks or craters
- Responsiveness to avoid rocks or craters
- Ease of maneuverability for crater rim crabbing
- Responsiveness for crater rim crabbing

- Ease of using the hand controller for driving operations
- Hand fatigue while using the hand controller
- Arm/shoulder fatigue while using the hand controller
- Overall acceptability of the hand controller to operate the LTV

The Acceptability Scale is based on a 10-point Likert scale (1-10) where the scale is divided into five distinct categories with two numerical ratings within each category to discriminate preferences (Figure 28). 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. Due to the small sample size, the team defined practical significance as a categorical difference on the Likert rating scale. Likert scale data can be considered as either interval or ordinal depending on the presentation of the rating scale to the subject [18]. 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 [18]. 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. The scale was used to describe how acceptable (or unacceptable) the hand controller(s) operated (e.g., to drive forward/reverse. Turn left/right, crab left/right, accelerate, brake, avoid objects, etc.) under the given South Pole lunar terrain and natural lighting conditions. Specific comments on desired/warranted/required improvement and/or minor/moderate/unacceptable deficiencies were noted for any numerical acceptability rating of 3 or higher.



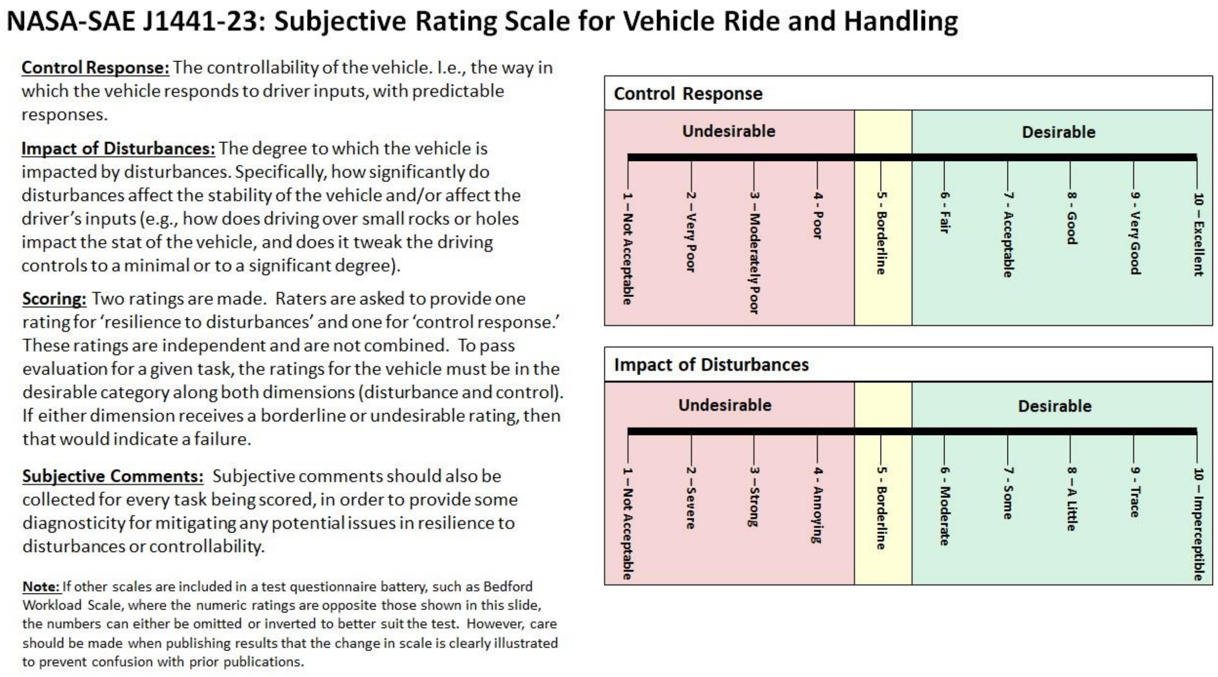
Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally Unacceptable	
No improvements necessary		Minor improvements desired		Improvements warranted		Improvements required		Major improvements required	
1	2	3	4	5	6	7	8	9	10

Figure 28. The Acceptability Rating Scale.

6.1.2 NASA's Society of Automotive Engineering (SAE) J1441-23 Subjective Rating Scale for Vehicle Ride and Handling

With the rover being essentially an off-road vehicle, human factors engineers will be using the NASA Society of Automotive Engineering (SAE) J1441-23 Subjective Rating Scale for Vehicle Ride and Handling. This coincides with the LTV/Pressurized Rover (PR) program desiring to use this particular scale instead of the aerospace standard of the Cooper Harper Handling Qualities Scale stating. The requirement states: "*The system shall exhibit desirable vehicle ride and handling performance, as defined by the NASA-SAE-J1441-23 Subjective Scale for Vehicle Ride and Handling. Desirable ratings of 6 to 10 are required for both 'Control Response' and 'Impact of Disturbances" for driving related tasks*."[19] The NASA-SAE-J1441-23 is a subjective rating scale for evaluating vehicle ride and handling. 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 [19]. As for the validity of the evaluation, it is restricted to individual ride and handling disciplines defined by the maneuver(s) and to the combination of vehicle conditions (e.g., equipment) and of the environment (e.g., road, weather)

[19]. NASA-SAE-J1441-23 provides the investigator a means to assign a numerical value to subjective judgments about the vehicle's ride and handling performance (Figure 29). The 'impact of disturbance' rating is an assessment of the degree to which instabilities are felt by the driver and/or affect 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 (raters) 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 [19]. Each task that the vehicle is being evaluated for is rated separately. 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. A frequency distribution of subjects will be presented in graph form.



NASA-SAE J1441-23: Subjective Rating Scale for Vehicle Ride and Handling

Control Response: The controllability of the vehicle. I.e., the way in which the vehicle responds to driver inputs, with predictable responses.

Impact of Disturbances: The degree to which the vehicle is impacted by disturbances. Specifically, 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 stat of the vehicle, and does it tweak the driving controls to a minimal or to a significant degree).

Scoring: Two ratings are made. Raters are asked to provide one rating for 'resilience to disturbances' and one for 'control response.' 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 along both dimensions (disturbance and control). If either dimension receives a borderline or undesirable rating, then that would indicate a failure.

Subjective Comments: Subjective comments should also be collected for every task being scored, in order to provide some diagnosticity for mitigating any potential issues in resilience to disturbances or controllability.

Note: If other scales are included in a test questionnaire battery, such as Bedford Workload Scale, where the numeric ratings are opposite those shown in this slide, the numbers can either be omitted or inverted to better suit the test. However, care should be made when publishing results that the change in scale is clearly illustrated to prevent confusion with prior publications.

Figure 29. The NASA-SAE-J1441-23 Subjective Rating Scale for Vehicle Ride and Handling.

6.1.3 The Cranfield Road Vehicle Dynamic Qualities Rating Scale (CRVDQRS)

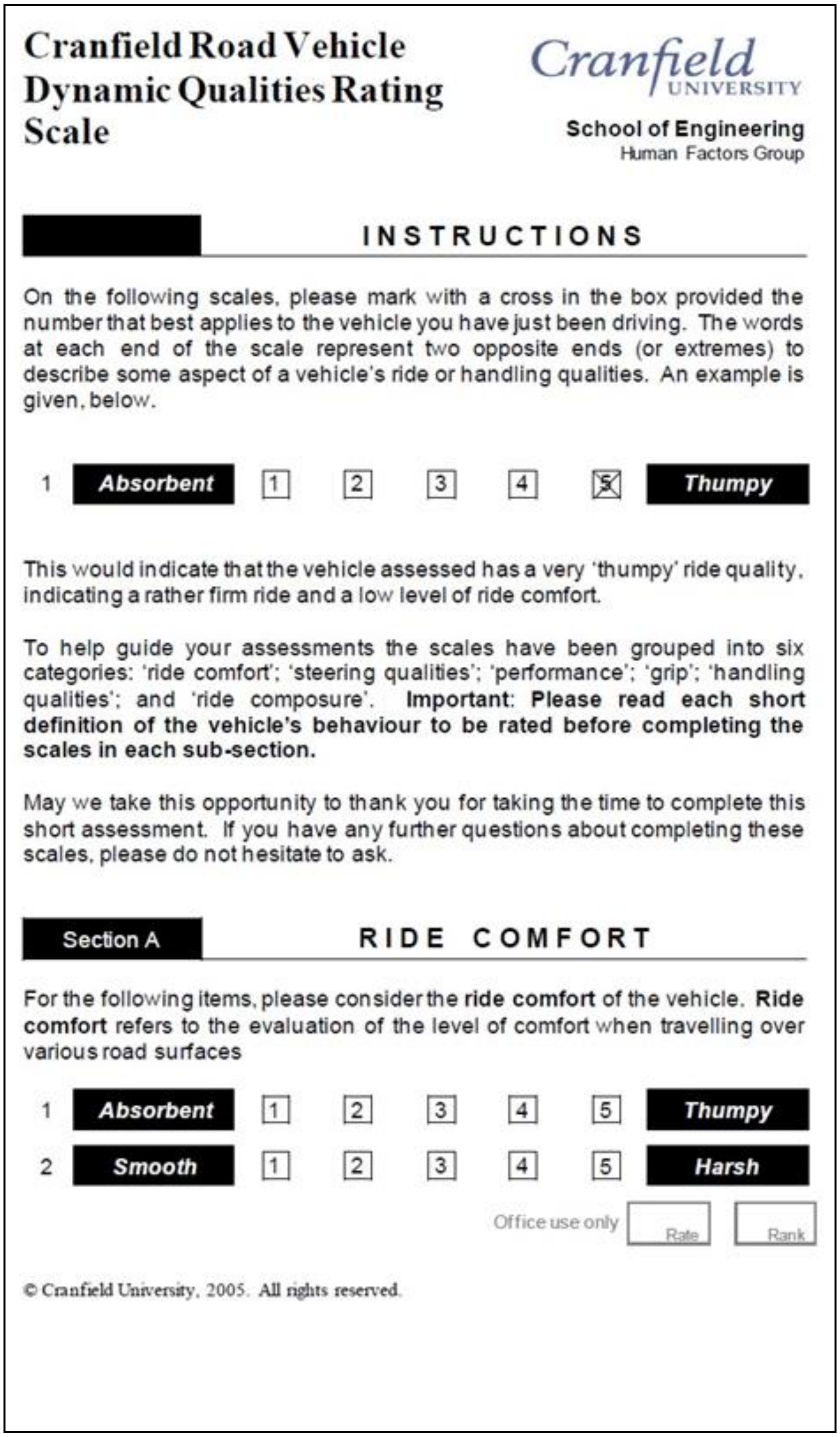
The Cranfield Road Vehicle Dynamic Qualities Rating Scale (CRVDQRS) was developed to emphasize the interaction between the vehicle's dynamic behavior and the category of vehicle [20]. Based off the Cranfield Aircraft Handling Qualities Rating Scale (CAHQRS) and NASA's Task Load Index (NASA-TLX) Harris, Chan-Pensley and McGarry (2005) [20] took into account the interaction between the vehicle's handling qualities and the task [21, 22, 23]. This is a different approach to vehicle handling qualities when compared to the unidimensional scales such as the

Cooper Harper Handling Qualities Scale and the Society of Automotive Engineers (SAE) J1441 Subjective Rating Scale for Vehicle Ride and Handling. 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 11 illustrates both the dynamic categories with their assigned bipolar anchor adjectives.

Table 11. *The CRVDQRS 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
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

Subjects would be prompted to mark the appropriate scoring box number that best applies to the vehicle they had just driven. The anchors at each end of the scale represents two opposite extremes to describe some aspect of a vehicle's ride or handling qualities (Figure 30). Subjects are asked to rate each category and sub-category. At the end of the questionnaire, the subject will be asked to rank the importance of each dimension of the vehicle's dynamic qualities. The importance scale comprises a ranking from 1 (most important) to 6 (least important) [20]. Sub-scale scores reflect a vehicle's dynamic qualities by calculating the product's mean scale value. A high rating represents a desirable ride or handling quality. The ranking data reflecting the importance of each of the dimensions for a particular category of vehicle.   A Friedman's Analysis of Ranks can be used to show any significant differences with regard to category of dynamic behavior assessed [20].



Cranfield Road Vehicle Dynamic Qualities Rating Scale

Cranfield UNIVERSITY

School of Engineering
Human Factors Group

INSTRUCTIONS

On the following scales, please mark with a cross in the box provided the number that best applies to the vehicle you have just been driving. The words at each end of the scale represent two opposite ends (or extremes) to describe some aspect of a vehicle's ride or handling qualities. An example is given, below.

1	***Absorbent***	☐ 1	☐ 2	☐ 3	☐ 4	☒ 5	***Thumpy***

This would indicate that the vehicle assessed has a very 'thumpy' ride quality, indicating a rather firm ride and a low level of ride comfort.

To help guide your assessments the scales have been grouped into six categories: 'ride comfort'; 'steering qualities'; 'performance'; 'grip'; 'handling qualities'; and 'ride composure'. **Important: Please read each short definition of the vehicle's behaviour to be rated before completing the scales in each sub-section.**

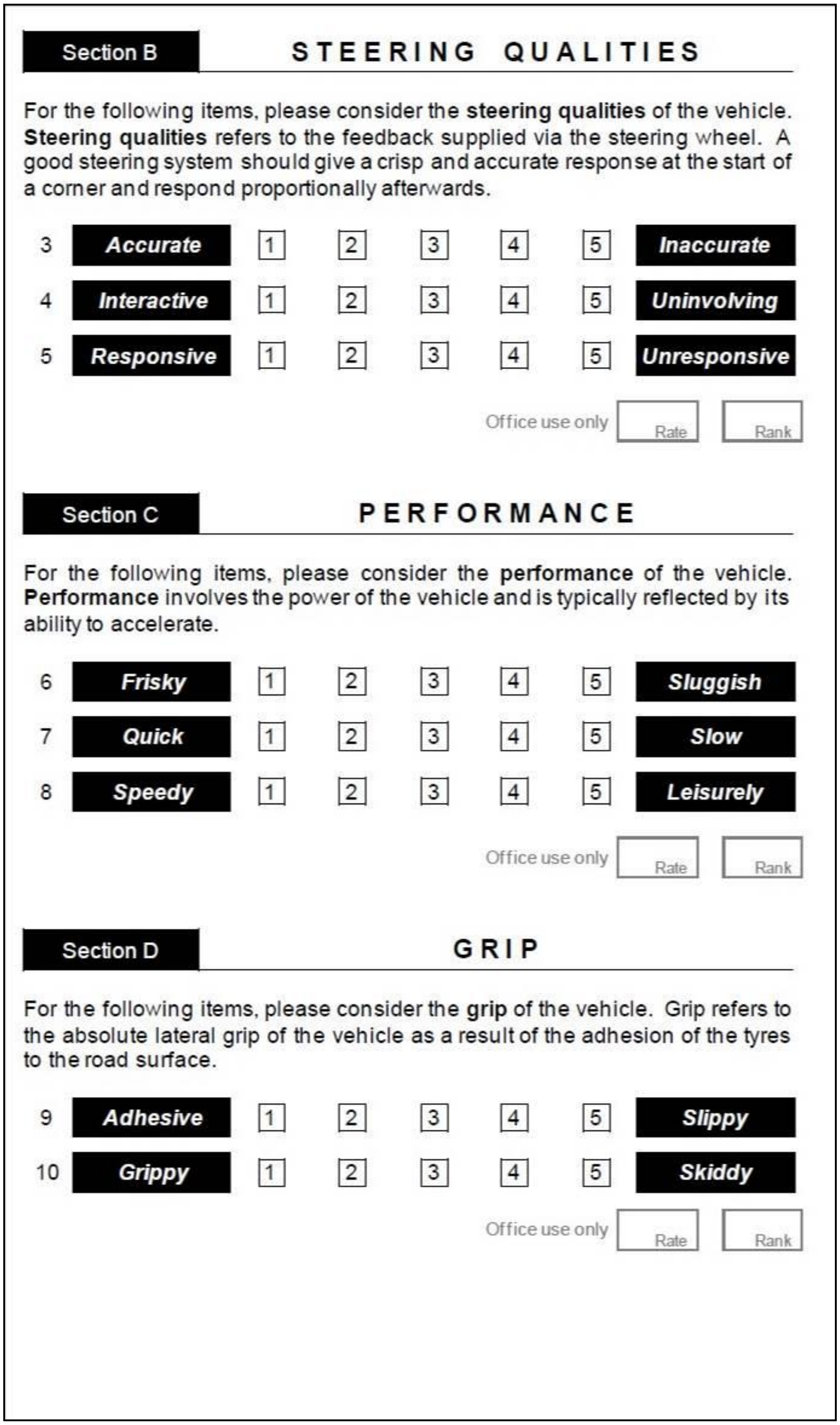
May we take this opportunity to thank you for taking the time to complete this short assessment. If you have any further questions about completing these scales, please do not hesitate to ask.

Section A RIDE COMFORT

For the following items, please consider the **ride comfort** of the vehicle. **Ride comfort** refers to the evaluation of the level of comfort when travelling over various road surfaces

1	***Absorbent***	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	***Thumpy***
2	***Smooth***	☐ 1	☐ 2	☐ 3	☐ 4	☐ 5	***Harsh***

Office use only ☐ Rate ☐ Rank



Section B STEERING QUALITIES

For the following items, please consider the **steering qualities** of the vehicle. **Steering qualities** 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.

3	**Accurate**	1	2	3	4	5	**Inaccurate**
4	**Interactive**	1	2	3	4	5	**Uninvolving**
5	**Responsive**	1	2	3	4	5	**Unresponsive**

Office use only ☐ Rate ☐ Rank

Section C PERFORMANCE

For the following items, please consider the **performance** of the vehicle. **Performance** involves the power of the vehicle and is typically reflected by its ability to accelerate.

6	**Frisky**	1	2	3	4	5	**Sluggish**
7	**Quick**	1	2	3	4	5	**Slow**
8	**Speedy**	1	2	3	4	5	**Leisurely**

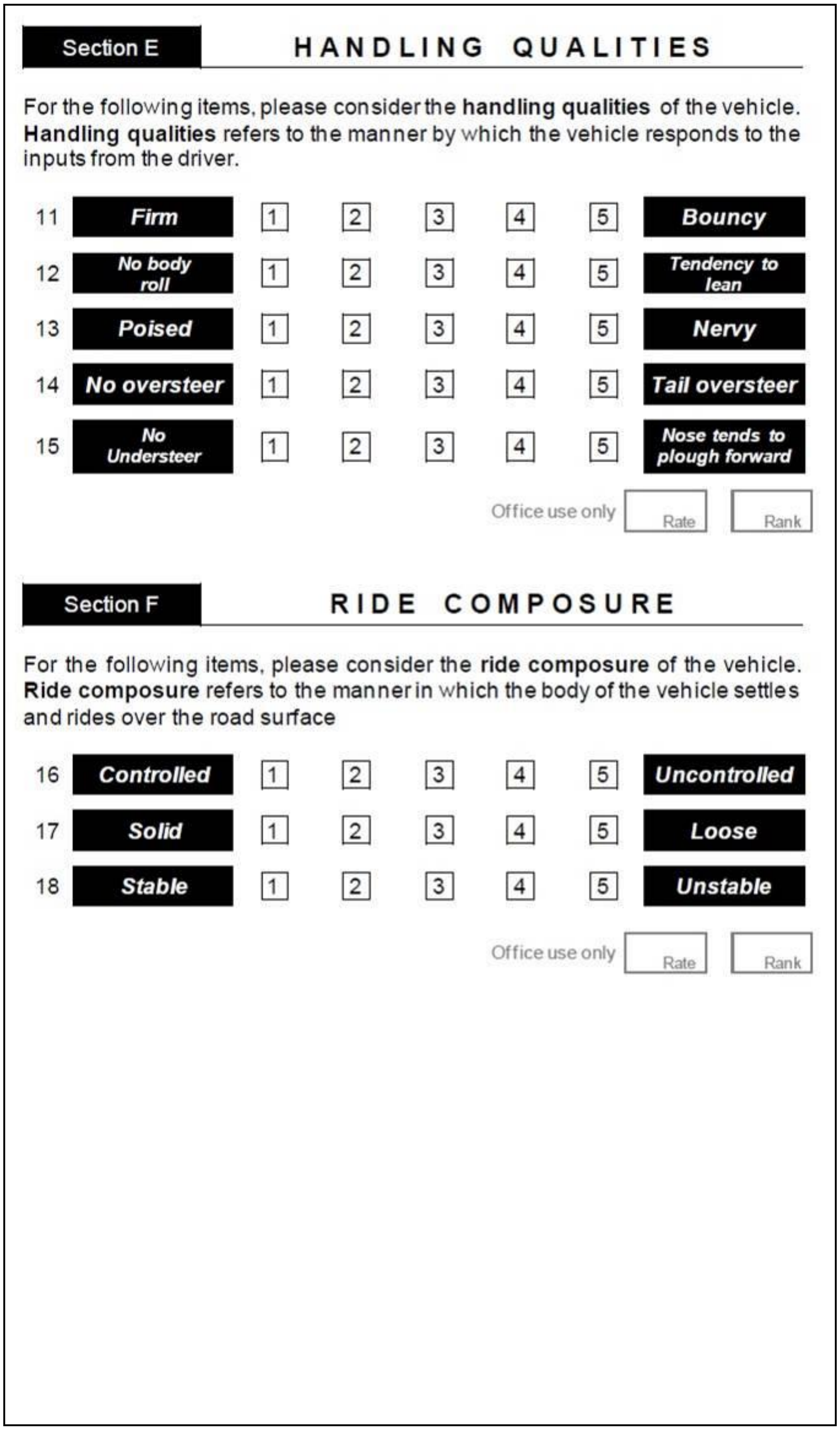
Office use only ☐ Rate ☐ Rank

Section D GRIP

For the following items, please consider the **grip** of the vehicle. Grip refers to the absolute lateral grip of the vehicle as a result of the adhesion of the tyres to the road surface.

9	**Adhesive**	1	2	3	4	5	**Slippy**
10	**Grippy**	1	2	3	4	5	**Skiddy**

Office use only ☐ Rate ☐ Rank



Section E HANDLING QUALITIES

For the following items, please consider the **handling qualities** of the vehicle. **Handling qualities** refers to the manner by which the vehicle responds to the inputs from the driver.

11	***Firm***	1	2	3	4	5	***Bouncy***
12	***No body roll***	1	2	3	4	5	***Tendency to lean***
13	***Poised***	1	2	3	4	5	***Nervy***
14	**No oversteer**	1	2	3	4	5	***Tail oversteer***
15	***No Understeer***	1	2	3	4	5	***Nose tends to plough forward***

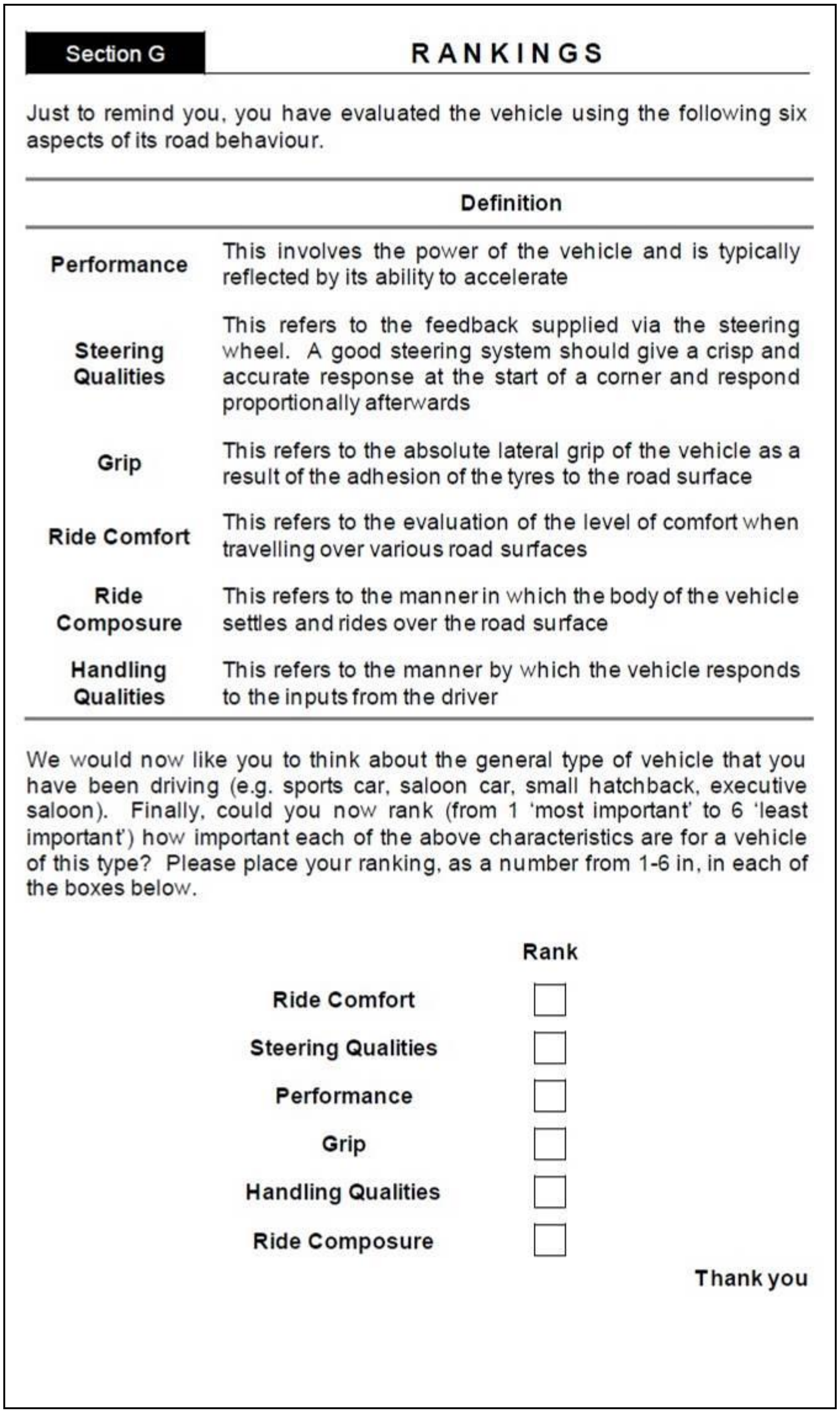
Office use only ☐ Rate ☐ Rank

Section F RIDE COMPOSURE

For the following items, please consider the **ride composure** of the vehicle. **Ride composure** refers to the manner in which the body of the vehicle settles and rides over the road surface

16	***Controlled***	1	2	3	4	5	***Uncontrolled***
17	***Solid***	1	2	3	4	5	***Loose***
18	***Stable***	1	2	3	4	5	***Unstable***

Office use only ☐ Rate ☐ Rank



Section G RANKINGS

Just to remind you, you have evaluated the vehicle using the following six aspects of its road behaviour.

	Definition
Performance	This involves the power of the vehicle and is typically reflected by its ability to accelerate
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
Grip	This refers to the absolute lateral grip of the vehicle as a result of the adhesion of the tyres to the road surface
Ride Comfort	This refers to the evaluation of the level of comfort when travelling over various road surfaces
Ride Composure	This refers to the manner in which the body of the vehicle settles and rides over the road surface
Handling Qualities	This refers to the manner by which the vehicle responds to the inputs from the driver

We would now like you to think about the general type of vehicle that you have been driving (e.g. sports car, saloon car, small hatchback, executive saloon). Finally, could you now rank (from 1 'most important' to 6 'least important') how important each of the above characteristics are for a vehicle of this type? Please place your ranking, as a number from 1-6 in, in each of the boxes below.

	Rank
Ride Comfort	☐
Steering Qualities	☐
Performance	☐
Grip	☐
Handling Qualities	☐
Ride Composure	☐

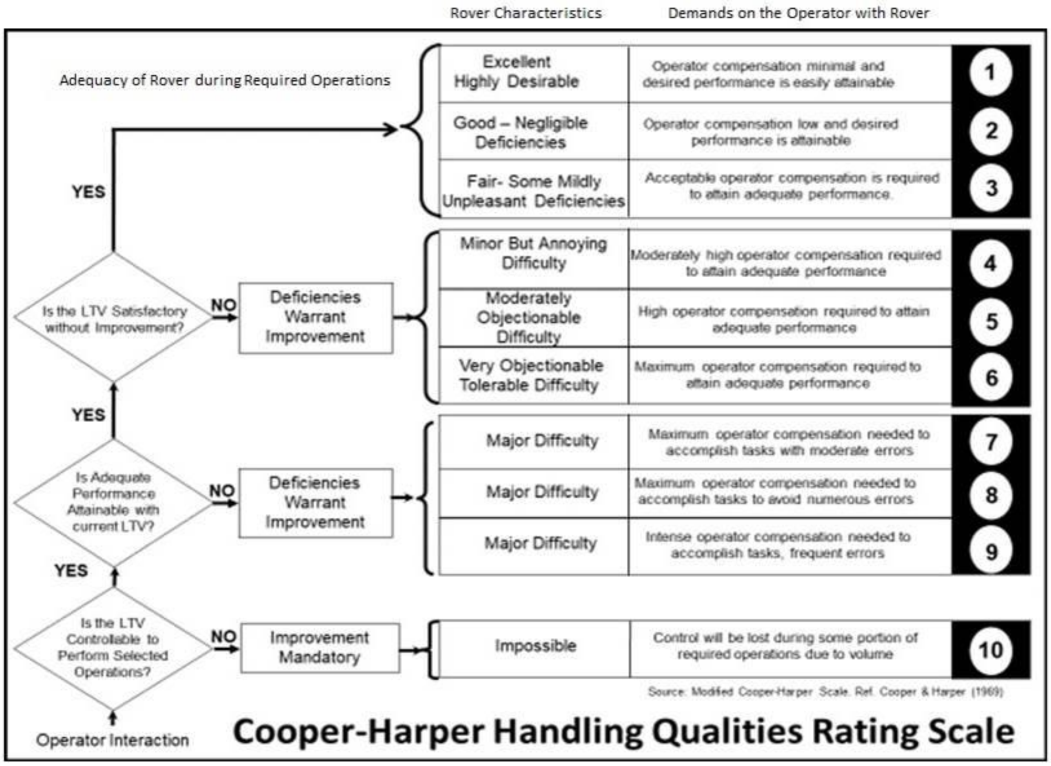
Thank you

Figure 30. The Cranfield Road Vehicle Dynamic Qualities Rating Scale (CRVDQRS).

6.1.4 The Cooper-Harper Handling Qualities Rating Scale

The Cooper-Harper Handling Qualities Rating Scale is a 10-point scale (1 – 10) from 1 meaning "easy, highly desirable" to 10 "impossible", across three levels (i.e., desirable, acceptable, and fail). This scale measures the level of crew accommodation to meet performance objectives (`Figure ***31***). These modified scales use the same levels as the original Cooper-Harper Handling Qualities Rating Scale [24] but have been modified to handling qualities of the LTV in terms of driving. To choose among the three rating levels, the subject follows a decision tree. There are different considerations depending upon where the decision tree answers led the subject [24, 25]. A Cooper-Harper rating of 1, 2, or 3 maps to Level 1 where performance is desirable, and the considerations are less discriminating. At this level performance achievement depends upon how taxed the operator is in producing that performance [24, 23]. 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. The scale should be easier accessible to the subject and the full decision tree should be traversed for each time a rating is given. Once a level has been selected, the subject should announce why each of the rating on that level is not proper for the evaluation at hand or why it should be considered. A frequency distribution of subjects will be presented in graph form.

TASK	D	A	F	NOTES
Traveling Time				
Traveling Errors				



`*Figure 31*. The Cooper-Harper Handling Qualities Scale.

Statistical analysis for comparing the three handling qualities scale will include a intra-class correlation coefficient (ICC) which is similar to an inter-rater testing, but in this case would be an inter-tool test. ICC's provide a measure of agreement of the items being assessed. The value of an ICC can range from o to 1, with 0 indicating no reliability among tools and 1 indicating perfect reliability among tools. Additionally, calculating separate correlations of each rating tool with the acceptability rating and the performance measures (driving time, number of driving mistakes/errors, etc.). With an ICC analysis, there are multiple models that can be employed for such correlation analyses. The two-way random effects model assumes that a group of *k* tools is randomly selected from a population and then used to rate the driving tasks. This model is often used to generalize the findings to any tools who are similar to the tools used in the study. There is also the two-way mixed effects model which assumes that a group of *k* tools is randomly selected from the population and then used to rate the driving tasks. However, what makes this model different from the two-way model is there is no interest in generalizing the findings to any other tools who might also share similar characteristics as the tools used in the study. In order to interpret the value of an intraclass correlation coefficient, this study will use Koo & Li [26] interpretation:

Less than 0.50 = a poor reliability
Between 0.5 and 0.75 = a moderate reliability
Between 0.75 and 0.9 = a good reliability
Greater than 0.9 = an excellent reliability

6.1.5 The Bedford Workload Rating Scale

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 32) [27, 28]. 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 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. When using the Bedford scale, each subject must be briefed as to the task they are rating, the time period over which to make the rating, and the other tasks for which they need to judge their spare capacity. These items need to be consistent across subjects for each task. The Bedford scale is not linear, and the underlying distribution is not predicted to be normal, thus calculation of a mean and median or the uses of parametric statistics are not appropriate. This verification requires that every subject's raw score is a 1, 2, 3, 4, 5, or 6 on the Bedford scale. The Bedford scale allows for half ratings (e.g., 1.5), which is also allowed here, as long as the rating is below a 6. A rating of 6.5 or higher is not acceptable for verification of a workload requirement. The Bedford workload scale will be used when using the NASA-SAE and Cranfield handling qualities scales. The Cooper-Harper is also a workload scale unto in itself. A frequency distribution chart will be created to analyze the workload ratings across handling quality scales.

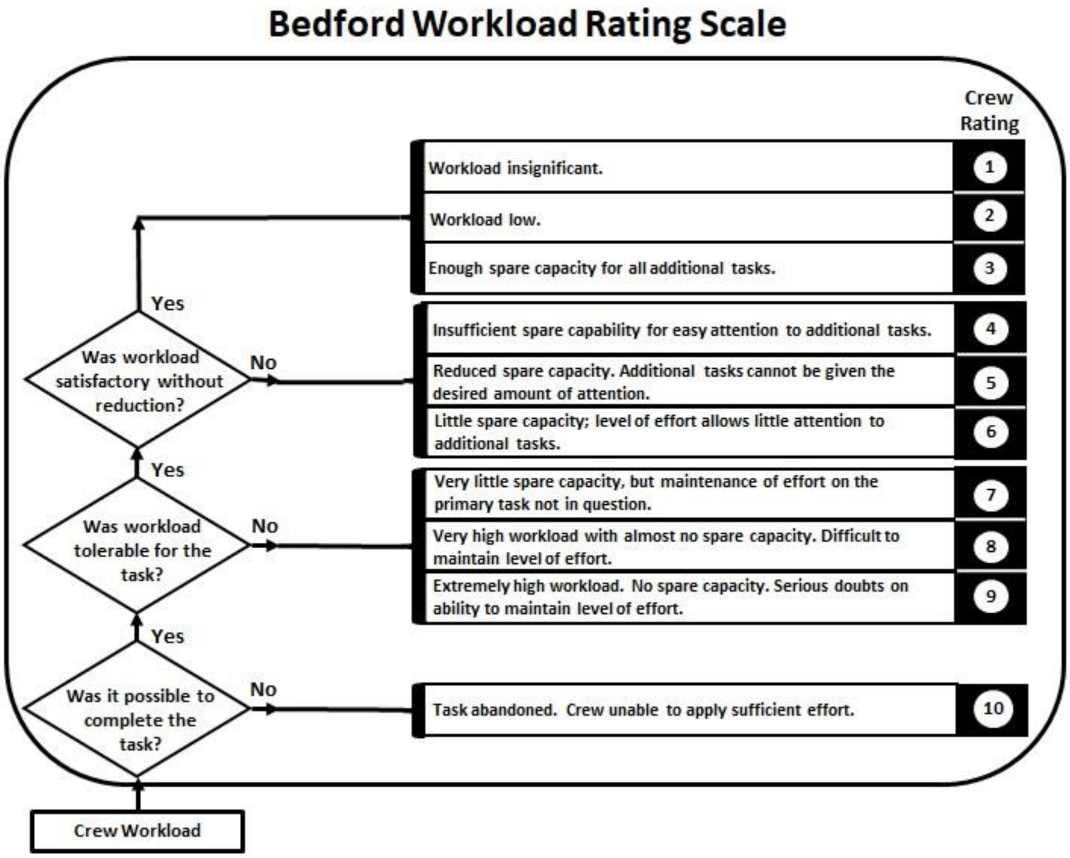
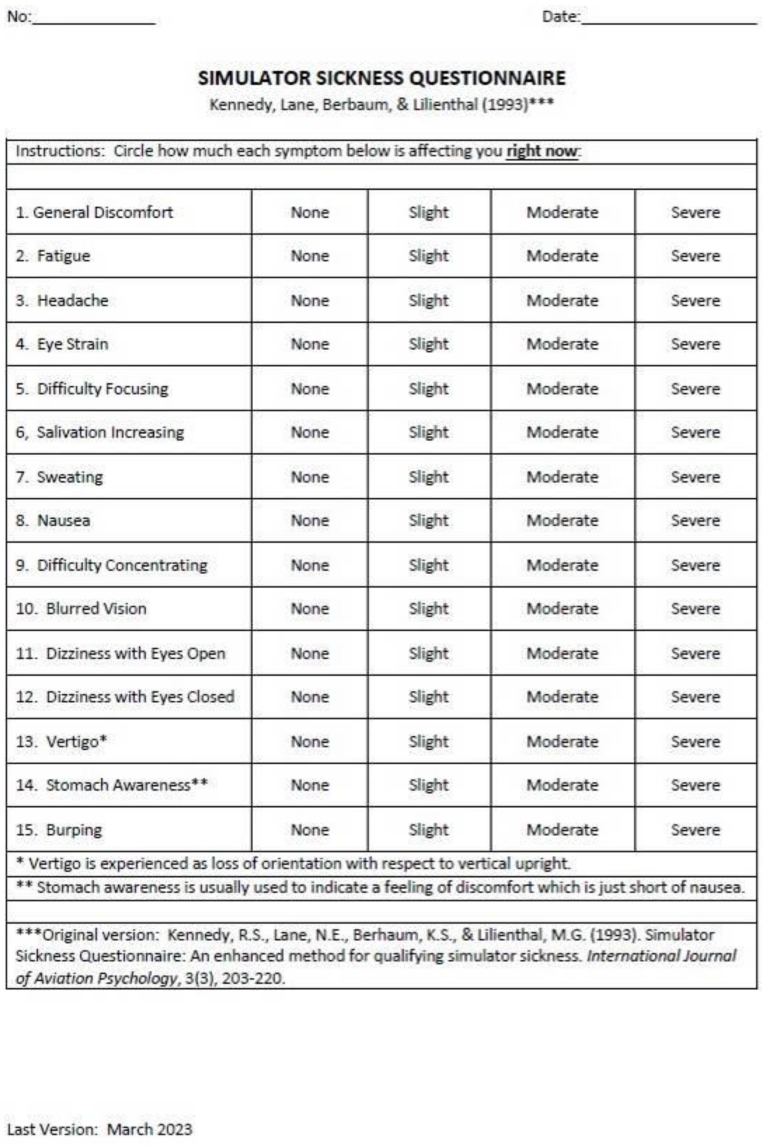


Figure 32. Bedford workload rating scale**.**

6.1.6 The Simulator Sickness Questionnaire (SSQ)

Balk, Bertola and Inman (2013) [29] states: "*Simulator sickness is generally the result of the discrepancy between simulated visual motion and the sense of movement stemming from the vestibular system*." Simulator sickness (SS) usually occur within the first 10 minutes of a simulation session and frequently can last for several hours afterward [30]. 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 [31]. This discrepancy is what causes many people to get simulator sickness. There are several ways to assess simulator sickness [29]; however, the most popular method is the Simulator Sickness Questionnaire (SSQ) published 20 years ago by Kennedy, Lane, Berbaum & Lilienthal (1993) [33]. The questionnaire asks the subjects to score 15 symptoms on a four-point scale (0-3) (Figure 33) [32].



No:_____________ Date:__________________

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 33. The Simulator Sickness Questionnaire (SSQ) [33]. Note in the original questionnaires there was another factor called Fullness of the Head. This factor was not defined in Kenney's papers; thus, the team decided to eliminate this factor. Other literature suggested this item was not a factor in SS [30].

Total scores can be associated with negligible (5), minimal (5 – 10), significant (10 -15) and < and concerning (15 – 20) symptoms [34]. If a total score is above 20, then the simulator/simulation is considered "bad." [35]. Kennedy et al. (1993) [33] noted that a factor analysis reveals these symptoms can be placed in three general categories: Oculomotor, Disorientation, and Nausea [26]. Weights are assigned to each of the categories and summed together to obtain a single score (Formula 1) [29].

Formula 1: SSQ Factor Analysis Formula

Where:

Nausea (N) = [1]

Oculomotor Disturbance (O) = [2]
Disorientation (D) = [3]
Total Score = TS
Scaling Factor = 3.74

TS = ([1] + [2] + [3]) x 3.74

It is encouraged to report means, medians, and standard deviations for all sub-scales and the total score [34]. 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 [29]. 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.

7.0 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-J1441 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).*

7.1. Simulator Sickness Data

Balk, Bertola, and Inman [29] 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 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. [27] Simulator Sickness Questionnaire (SSQ) [36]. 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 every 10 minutes during the driving activity and at the end of each 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 [37] factor analysis studies 1988 [37, 38,39,40], 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 [36] which are all related to gastrointestinal distress [40]. The oculomotor (O) cluster includes fatigue, eyestrain, difficulty focusing and headache [40]. As for disorientation (D) revolves are blurred vision, vertigo, and dizzy with eyes opened and eyes closed [36]. 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 [40] simulator troublesome index (Table 12).

Table 12. *Simulator Troublesome Index*

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

Kennedy, Drexter, Compton, Stannely, Lanham, and Harm (2003) [40]

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 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 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 13).

Table 13. *Average Scores of Simulator Sickness*

	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. When asked to rate the acceptability of the two environments, driver indicated it was totally acceptable with no improvements necessary (Mdn = 2). 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.

Drivers agreed there was little effects of simulator sickness during the Test Track session. They recounted with the short bursts of the Test Track 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 easy any discomfort they made have felt. The test drivers did take a 10-to-15-minute break between courses. The long traverse course seems to be where 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 (IQR = 142.7, 2,008.6 meters) within a median time of 2,528 seconds (IQR = 1,119, 2,851 seconds) or 42 minutes and 8 seconds. The majority of the symptoms reported was nausea and stomach awareness while driving the long traverse. 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. 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 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 drivers who experienced it. Some drivers notice the visuals were slight off with the physical motion and jittery. This occurred when the driver was trying to concentrate on navigating the terrain and the visual simulation seen to have difficulty coupling with the physical movement cause disorientation. For some drivers, accelerating the vehicle too fast could cause light headiness as well. There were some minor oculomotor affects that drivers reported. With the visual artifacts and the movement of the table during this long traverse, drivers indicated a descent 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 with some individuals' symptoms increasing in severity and become noticeably unpleasant for the driver [41]. Conversely, some studies have shown simulator sickness in some individual begins to stabilize [42] or even decrease over time [43] as they adapt to the VR environment [44]. However, researchers agree adaptation to the VR environment appears feasible, but more study is required on this issue.

Using human drivers while testing controlling aspects of a lunar rover in a 1/6g lunar environment prove invaluable to the motion table testing facility. This was the first regress test the new facility had conducted; thus, numerous lessons were learned during this testing period. Table 14 illustrates the lesson capture during testing to increase the facilities fidelity and capabilities.

Table 14. *SES Motion Table Issue/Enhancement Tracker* (11 July 2023)

Number	**Short Description**	**Long Description**	**Status**	**Actions Taken So Far:**	**Forward Work:**
1	SA Signature Delay	Had to delay start of study waiting on signatures from SA.			Need to coordinate better with signees to make sure everything signed in timely manner. Identify backup for each signee and make sure they are included on all correspondence such that they can jump in at short notice if needed.
2	Scene Flashing with HTC Vive Pro 2	During some of the early sessions, tried to switch to HTC Vive Pro 2 (vs. HTC Vive) for better resolution and performance, but had issues during 6/8/23 session with		Reverted to using HTC Vive Pro headset for study. Tried to reproduce during dev session on 7/10/23. Gray flashing happens when sensors on top sides of VR	Will continue to use Vive Pro 2 for upcoming training sessions and see if problem can be reproduced. May need to verify hair and wires are clear of sensors when first putting on headset and

Table 14. *SES Motion Table Issue/Enhancement Tracker* (11 July 2023)

Number	Short Description	Long Description	Status	Actions Taken So Far:	Forward Work:
		gray flashes intermittently showing up in FOV, so stopped using it.		headset are obstructed - thinking that maybe MTP's hair or the ClearCom microphone wire might have been occasionally occluding sensor.	verifying clear if issues occur.
3	Added 2 New Teleport locations	Chip requested two new teleport locations. Cory implemented these into the sim, but they still need to be added to DcApp in the Mini Dome copy of the Rover sim release	Partial Fix	Used Trick View to execute teleportation to two new locations	Need to update sim to include these such that they can be executed via DcApp
4	VR Graphics Flip	VR Graphics occasionally appears to momentarily flip (maybe due to tracking drop?).		Tried installing tracker in different locations, increasing trackers, increasing number of base stations, but problem still occurs occasionally.	Simulation Team may have potential fix. Need to test.
5	Table rotation not matching DCApp display for angles > 10deg	When driving on sloped terrains, pitch and roll values on Dcapp display match pretty well with Pitch and Roll values in Safety Monitor and Mikrolar for low angles (< 11 deg), but then seem to diverge at higher angles. The SESMT angles are significantly smaller (ex. 20 on display, vs. 13 in table).	In Work	Mathematical had some updates to the software that allowed better matching of angles. Tom tested updates with Motion Table on 7/10/23, and overall seemed to be an improvement, but had two unexplained violent E-stops, so there appears to be a bug or something that we need to track down before it will be ready for use.	Could have to do with margins of error for physical limits of table.
6	TOP tracker data spike causes Safety Monitor triggered E-Stop	Occasional data spikes in tracked data trigger E-Stop and necessitate egressing participant from table in awkward positions.	In Work	Move base station and trackers under table, which seemed to offer big improvement, but still happens occasionally	Improve tracking, implement some way to filter data spikes and to recover from E-stop without egressing participant?

Table 14. *SES Motion Table Issue/Enhancement Tracker* (11 July 2023)

Number	**Short Description**	**Long Description**	**Status**	**Actions Taken So Far:**	**Forward Work:**
7	Motion on flat terrain seems unrealistically smooth	Doesn't give true sense of motion since there is no rumble/vibration. Due to 5m terrain data. Shouldn't be an issue with different terrain.		Problem is that the area of terrain they are driving on is low resolution, so doesn't have enough details to drive realistic motion.	Test Team will try to find a better area of the terrain for this test for future study runs.
8	Feet dangling while sitting in chair on SESMT	SESMT chair is high enough off the platform that most average or small sized participants feet do not reach the platform and therefore dangle.	Fixed	H/W team implemented foam footrest that can be adjusted by adding/removing layers of foam.	Need to figure out better way to adhere Velcro to foam as it tends to come unglued when separating layers.
9	Forced System & Software updates	The Windows systems seem to still be auto-updating, which has caused issues in the past. Screen-lock also seems to keep getting re-enabled which can also cause issues/glitches.	In Work	S.A. Team has been notified to disable automatic updates on Mini Dome systems.	S.A. Team will ensure all Mini Dome systems are setup to prevent automatic updates and will notify SES personnel when updates are made so that time can be reserved for testing/troubleshooting.
10	Some people had issues with Lumbar support on chair	With the VR headset on, the back knob touches the seatback, so people tend to want to recline the seat back more such that their head is more level, but then that causes a gap between their back and the lumbar support on the seat.	Partial Fix	Brought in a small pillow to offer to people that need it.	Would be good to get better pillow/cushion for this long term.
11	Occasional thud/knock noise from table.	Sometimes when table is in motion, the table will make a clunk that is similar but not as severe as what you hear when engaging E-Stop. It doesn't appear to affect the table motion but could be a concern for health of the table.	In Work		Tom looking at logging timing issues. Sim Developer recommends looking at core isolation for sim (would probably require kernel update). Lee and JB have done core isolation for other facilities and can try that here as well.
12	Motion in crabberman	Table moves around a lot in a swaying			

Table 14. *SES Motion Table Issue/Enhancement Tracker* (11 July 2023)

Number	Short Description	Long Description	Status	Actions Taken So Far:	Forward Work:
	mode seems unrealistic	motion. Motion in sim itself also appears to be unrealistic at times.			
13	Noise from table distracting when it doesn't match visuals	For certain motions, the motion and subsequent noise from the table doesn't seem to correspond with the observed motion which messes with people's heads. Would be good if we could find a way to block out all noise from table.			
14	Cannot easily recover from inadvertent move to home/load on GUI resulting in mismatch with Motion Program and SESMT	On a few occasions, the SMTO inadvertently cleared errors (which moves table to home) while in LOAD position, which caused a mismatch in table positions between programs and required egress to clear.			Should be fixed when we updated to latest version of the Motion program?
15	Map traverse trail in sim doesn't always match VR version.	The blue path shown on the DCAPP display does not exactly match the virtual trail in VR that is shown to the test subjects, which makes navigating more difficult.			Need to update one or both of them to be consistent.
16	VR Position Drift	Saw during Epic Games demo due to poor tracking			Will try to investigate, but best solution is to fix tracking issues.
17	Add Dynamic map and cruise control status in VR display.	Currently the display in VR shows rover mode, speed and brake status and has a static map. Would like to have dynamic map and for the cruise control status and speed to be displayed.			

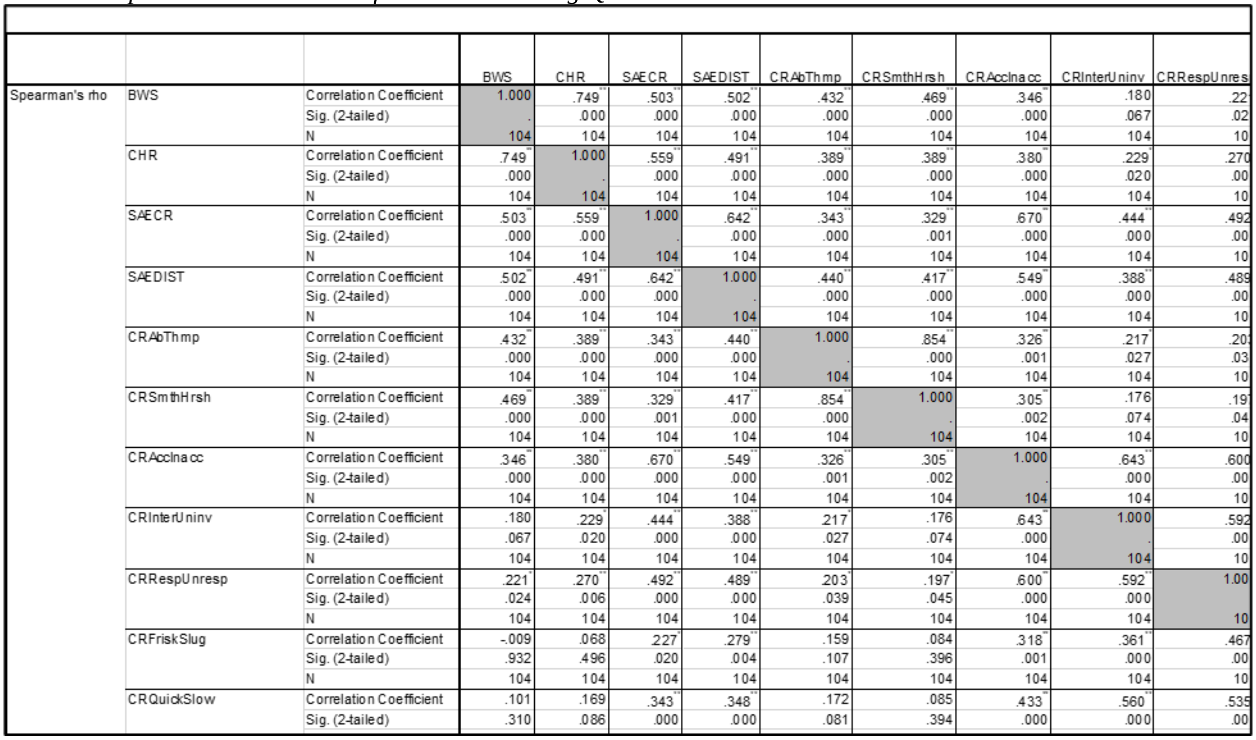
Table 14. *SES Motion Table Issue/Enhancement Tracker* (11 July 2023)

Number	Short Description	Long Description	Status	Actions Taken So Far:	Forward Work:
18	Route DCApp visuals to Teams and SMTD console	Currently SMTD has look around pole to monitor DCApp display. Would be nice if the DCApp display could be routed into Teams and also be available as part of the view at the SMTD console.			

7.2. Handling Quality Method Analysis

For the handling qualities scale analysis, a Spearman Rho Correlation analysis was conducted. This analysis measures the strength to association between two variables. The coefficient range for a Spearman correlation is -1 to +1. In this case, all of the correlations were positive in nature meeting that as one variable increases, the compared variable also increases. An example of the correlation relationships for the three handling qualities which were tested can be seen in Table 15 while a more complete table is in Appendix C. As a baseline, traditionally the Cooper-Harper Handling Qualities Rating Scale correlates extremely with the Bedford Workload Rating Scale with up to 70 to 80% agreement [48, 49]. With this study, the Spearman correlation was computed to assess the relationship between the Cooper-Harper and Bedford scales, There was a positive correlation between the two scales r(12) =.749, p =.05 giving the test team a high level of confidence. The comparison between the Cooper-Harper and the SAE-J1441 scales indicated a positive relationship r(12) = .559 (control response) and r(12) = .491 (impact of disturbance), p = 0.5. The correlation relationship between the two SAE-J1441 scales was r(12) = .642, p = .05. The reason for the lower correlation with the SAE impact of disturbance and the Cooper-Harper is they do not measure the same attributes. However, the correlation between the controllability aspect of the SAE to the Cooper-Harper is good. As for the Cranfield handling qualities scale, it did not really correlate very well with any of the other scales. The recommendation of the Spearman correlations reveals the SAE-J1441 is the scale to use for planetary rover handling qualities. The rational for this scale is it strictly a vehicle dynamic qualities scale. The team also recommends using the Bedford Workload scale in conjunction with the SAE-J1441 as the Bedford looks at the task and interface combined to reveal how much workload is required for the task, while the SAE-J1441 examines the controllability and disturbance resistance on how the vehicle handles and performance on surfaces in specific tested environments.

Table 15. *Spearman Correlations for Three Handling Qualities Scales and a Workload Scale*



			BWS	CHR	SAECR	SAEDIST	CRAbThmp	CRSmthHrsh	CRAccInacc	CRInterUninv	CRRespUnres
Spearman's rho	BWS	Correlation Coefficient	1.000	.749**	.503**	.502**	.432**	.469**	.346**	.180	.22
		Sig. (2-tailed)	.	.000	.000	.000	.000	.000	.000	.067	.02
		N	104	104	104	104	104	104	104	104	10
	CHR	Correlation Coefficient	.749**	1.000	.559**	.491**	.389**	.389**	.380**	.229*	.270
		Sig. (2-tailed)	.000	.	.000	.000	.000	.000	.000	.020	.00
		N	104	104	104	104	104	104	104	104	10
	SAECR	Correlation Coefficient	.503**	.559**	1.000	.642**	.343**	.329**	.670**	.444**	.492
		Sig. (2-tailed)	.000	.000	.	.000	.000	.001	.000	.000	.00
		N	104	104	104	104	104	104	104	104	10
	SAEDIST	Correlation Coefficient	.502**	.491**	.642**	1.000	.440**	.417**	.549**	.388**	.489
		Sig. (2-tailed)	.000	.000	.000	.	.000	.000	.000	.000	.00
		N	104	104	104	104	104	104	104	104	10
	CRAbThmp	Correlation Coefficient	.432**	.389**	.343**	.440**	1.000	.854**	.326**	.217*	.20
		Sig. (2-tailed)	.000	.000	.000	.000	.	.000	.001	.027	.03
		N	104	104	104	104	104	104	104	104	10
	CRSmthHrsh	Correlation Coefficient	.469**	.389**	.329**	.417**	.854**	1.000	.305**	.176	.19
		Sig. (2-tailed)	.000	.000	.001	.000	.000	.	.002	.074	.04
		N	104	104	104	104	104	104	104	104	10
	CRAccInacc	Correlation Coefficient	.346**	.380**	.670**	.549**	.326**	.305**	1.000	.643**	.600
		Sig. (2-tailed)	.000	.000	.000	.000	.001	.002	.	.000	.00
		N	104	104	104	104	104	104	104	104	10
	CRInterUninv	Correlation Coefficient	.180	.229*	.444**	.388**	.217*	.176	.643**	1.000	.592
		Sig. (2-tailed)	.067	.020	.000	.000	.027	.074	.000	.	.00
		N	104	104	104	104	104	104	104	104	10
	CRRespUnresp	Correlation Coefficient	.221*	.270**	.492**	.489**	.203*	.197*	.600**	.592**	1.00
		Sig. (2-tailed)	.024	.006	.000	.000	.039	.045	.000	.000	
		N	104	104	104	104	104	104	104	104	10
	CRFriskSlug	Correlation Coefficient	-.009	.068	.227*	.279**	.159	.084	.318**	.361**	.467
		Sig. (2-tailed)	.932	.496	.020	.004	.107	.396	.001	.000	.00
		N	104	104	104	104	104	104	104	104	10
	CRQuickSlow	Correlation Coefficient	.101	.169	.343**	.348**	.172	.085	.433**	.560**	.535
		Sig. (2-tailed)	.310	.086	.000	.000	.081	.394	.000	.000	.00

The intercorrelation analysis indicated the Cooper-Harper and SAE 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 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-J1441 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-J1441 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 16). 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 16. *SAE-J1441 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

7.2.1. Test Track Task Results and Discussion

These sections will discuss the results of the Test Track Course. The Acceleration and Maintaining Max Speed Task (Task 01) will be 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. Task 02 is the Braking and Sliding Distance Task. This task is also broken into two segments: 1) First Brake at Max Speed and 2) Sliding Distance to Vehicle Stop. Braking tasks are extremely important for any vehicle; thus, these tasks test the vehicle's ability to hard brake if the vehicle is a max speed and to calculate, it any, the distance the vehicle slides through the braking process to achieve a full vehicle stop. The Crater Field Avoidance Task (Task 03) is a classic object avoidance task. With the Constant Lateral Turn 360-Degree Task (Task 04), 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. Task 05, the Crater Rim Driving Task, is the only crabbing mode driving task the drivers accomplish on the Test Track Course. This task will examine the vehicle's ability to drive around a crater rim with the nose of the vehicle standing centered on the crater's center. Testing both the vehicle and hand controllers maneuverability aspects, the driver must maintain a pre-determine speed and pre-determined distance from the crater rim while also avoiding obstacles. Finally, Tasks 06-08 are slope driving tasks that exercises the vehicle's handling for slopes 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.

7.2.1.1. Task 01- Acceleration and Max Speed on Straight Level Terrain

Currently none of the LTV models, virtual or physical, has done any road handling tests. Thus, with the GTU being assembled, the virtual vehicle was used. In the automotive world, the straightforward tasks measure several items of interest. From a lunar perspective, Apollo 15 reported when they accelerated the LRV on the lunar surface "*it was smooth with very little wheel slippage.*" [45]. The amount of time it takes a vehicle to accelerate to a certain speed from a dead stop and could the vehicle maintain that speed for a certain distance. The test drivers drove a 300-meter distance for this task. The terrain was avoided of any obstacles and fairly flat. 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

17). 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. To coincide with the median score, the drivers rated the task as *acceptable with minor improvement desired*. The majority of the test drivers found maintaining the max speed was simple and easy. They reported the vehicle response was good to the movement; however, the hand controller used was not super sensitive and would not act immediately. Once at max speed some drivers reported they felt the vehicle was going slower than what was indicated on the display. It was noted that manually keeping the hand controller at max deflection was fatiguing and it was sometimes difficult to maintain one's hand position without effecting the maintenance of the speed. It was also 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. Though the task was accomplished on a relative flat, level terrain, there were some anomalies in the elevation which could have caused the vehicle to feel a little out of control. Overall driver workload for this task was consider by drivers as insignificant (Mdn = 1). This positions the workload on the Bedford Workload Scale as a Level 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 17. *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 18). 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 18. *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

7.2.1.2. Task 02 - Braking /Sliding Distance Task on Straight Level Terrain

Braking tasks are also a main stay in the automotive world examining, at certain speeds, braking distances. 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*." [45] 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.

Investigators were 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*."[45]. 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 19). 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 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." Other drivers observed the 1/6-g lunar gravity environment affected how long it took the vehicle to stop. 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. 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 19. *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

7.2.1.3. Task 03 – 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."* [45]. 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 20). This concurs with what Apollo 15 reported; "*For obstacle avoidance, the optimum technique was to slow [the LRV] down to below 5 kph*."[45] As for the acceptability of the vehicle to avoid terrain features such as rocks or craters, drivers rated the vehicle *acceptable with minor improvements desired*. 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 mode steering, 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 20. *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

7.2.1.4. Task 04 – Constant Lateral Turn 360-Degree 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 in took test drivers 126 seconds to traverse 165.4 meters around the lander at 4.5 kph (Table 21). Drivers rated the acceptability of the task as *acceptable with minor improvements desired*. 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 in 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 21. *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

7.2.1.5. Task 05 – 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. During engineering testing, the test team used the same crater at Bear Paw that was previously used in an earlier hand controller design test. What made this 35-meter diameter crater interesting was the buildup of the slopes around the rim from 3 to 20-degrees. This truly exercised the crab mode; however, due to several of the engineer subjects not able to complete the task due to some issues with the joystick controller and the LTV modeled motor controllers, the test team chose a simpler crater so that the task could be completed, and some preliminary data could be collected. 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 mode steering 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 22). Drivers rated the acceptability of the task as *borderline with improvements warranted*. 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.

Table 22. *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

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. This is due in part by the large amount of movement that needs to take place in order to crab and crabbing seems to be highly affected by unexpected jerks in hand controller inputs especially with turning on a rocky terrain.

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.

7.2.1.6. Task 06 – 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*." [46] 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*." [47] 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 [45,46,47] Median performance stats for this tasked showed a speed of 5.67 kph going down a 232.9-meter slope taking 145 seconds (Table 23). Drivers rated the acceptability of the task as *totally acceptable no improvements necessary*. 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*". [45] 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 23.. *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

7.2.1.7. Task 07 – 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*." [46] 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*." [47] 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 [47]. 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 24). 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*." [47] Drivers rated the acceptability of the task as *totally* *acceptability with no improvement necessary*. 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."* [45] As with the down slope task, the workload for the cross slope driving task (Mdn = 2) indicating workload was considered low. Drivers indicated this was an easy task as they were just maintaining their speed and hand controller inputs.

Table 24. *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

7.2.1.8. Task 08 – 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."* [45] 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*."[47] 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*." [46] 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*." [45] 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 25). 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."* [47] Drivers rated the acceptability of the task as *totally acceptable with no improvements necessary*. 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. This also affect the speed of the vehicle and maintaining a constant speed up the hill was a little more challenging than the down slope situation. Driver conveyed their workload was low and manageable (Mdn = 2) as their workload was tied to the terrain they traversed. This pulled most of their attention to maintaining control of the vehicle as there was some flighting with the hand controller inputs. Maintaining speed was also a factor in their workload. However, drivers did feel the workload was manageable.

Table 25. *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

7.3. Long Traverse Course Analysis

The long traverse course brings all the elements of the Test Track together into a single 5 km course with the added experience of 1/6g, expected lunar terrain features, lunar hardware, and lunar South Pole lighting conditions. A pre-determine navigation route was set for the drivers. Drivers were encouraged to use all capabilities available to them such as cruise control, Ackermann steering, crab mode steering, and display information. During the approximately hour long run, a test conductor aided the driver as a co-pilot for certain navigational partition of the course. The analysis of the long transverse will be broken into two segments: 1) overall analysis of the traverse using all test drivers and 2) complete analysis of course using only the five drivers who were able to finish the course.

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. Of all the driving tasks accomplished by the driver, this one tests the ultimate challenges with handling the vehicle. 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. However, this does not clearly represent the five drivers who did finish the course. Therefore, the test team conducted another descriptive analysis on just the five drivers who finished 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 26). The speed still concurs with what the Apollo LRV crew noted for rough terrain. For this task, drivers did not rate the acceptability of the task 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.

Table 26. *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

Terrain was definitely a factor when handling qualities are concerned, especially with this longer traverse course (Figure 34). There were instances where the terrain tended to push the vehicle around and would bounce the driver around sometimes violently on the motion table. Navigating around craters did not seem to be an issue; however, the continuous bouncing off rocks was indicated as being the problem with controlling the vehicle. 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.* " [45] 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. Drivers reported they had an idea of where they were going but not how to get there. 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. Drivers noted that with the co-pilot, they would point out craters the driver did not see and would the driver navigate the area around craters. 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.

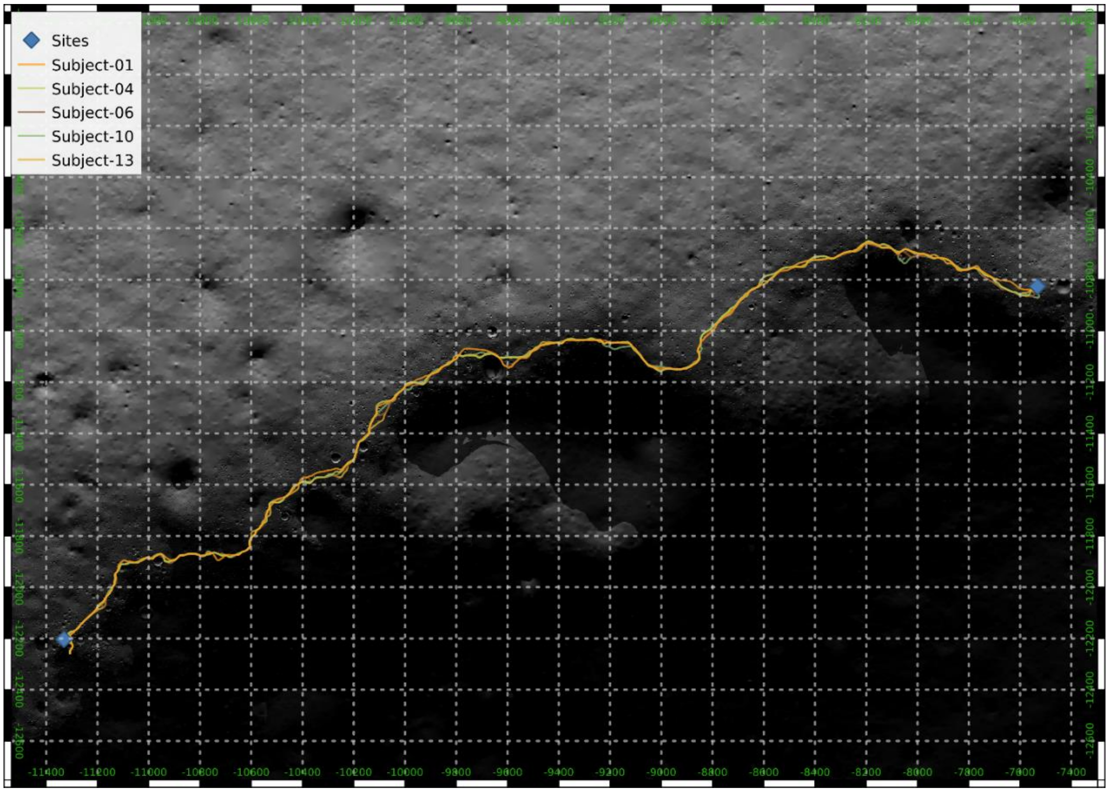
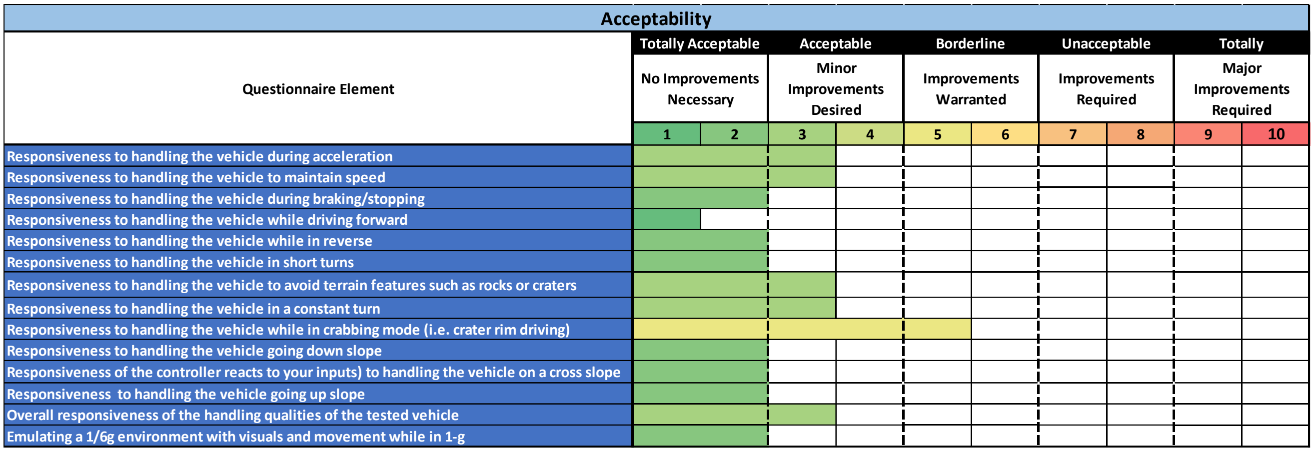


Figure 34. Traverse paths of the five drivers who made the total 5 km course up to the lunar lander site.

7.4. Subjective Overall Acceptability

Overall, the responsiveness of controlling the vehicle was considered by drivers as good (Figure 35). However, to further improve the handling quality of the government referenced LTV drivers offer a few suggestions to consider. First, hand controller used for this study made certain movement very difficult to achieve. Specifically, with the crabbing function as it was rated *borderline with improvements warranted*. Acceleration and speed maintainability likewise exhibited complications or glitches. To improve these anomalies separate control inputs for Ackermann steering and crab could be valuable in having more control over each input especially when dealing with more complex terrain. Hand controller sensitivity could be improved by adding a way to adjust the sensitivity at the controller. Having a cruise control function to maintain speed and ease the driver's inputs would likewise be useful to reduce workload on the driver.



	Acceptability									
Questionnaire Element	Totally Acceptable		Acceptable		Borderline		Unacceptable		Totally	
	No Improvements Necessary		Minor Improvements Desired		Improvements Warranted		Improvements Required		Major Improvements Required	
	1	2	3	4	5	6	7	8	9	10
Responsiveness to handling the vehicle during acceleration	🟩	🟩	🟩							
Responsiveness to handling the vehicle to maintain speed	🟩	🟩	🟩							
Responsiveness to handling the vehicle during braking/stopping	🟩	🟩								
Responsiveness to handling the vehicle while driving forward	🟩									
Responsiveness to handling the vehicle while in reverse	🟩	🟩								
Responsiveness to handling the vehicle in short turns	🟩	🟩								
Responsiveness to handling the vehicle to avoid terrain features such as rocks or craters	🟩	🟩	🟩							
Responsiveness to handling the vehicle in a constant turn	🟩	🟩	🟩							
Responsiveness to handling the vehicle while in crabbing mode (i.e. crater rim driving)	🟨	🟨	🟨	🟨	🟨					
Responsiveness to handling the vehicle going down slope	🟩	🟩								
Responsiveness of the controller reacts to your inputs) to handling the vehicle on a cross slope	🟩	🟩								
Responsiveness to handling the vehicle going up slope	🟩	🟩								
Overall responsiveness of the handling qualities of the tested vehicle	🟩	🟩	🟩							
Emulating a 1/6g environment with visuals and movement while in 1-g	🟩	🟩								

Figure 35. Drivers overall median acceptability scores for vehicle responsiveness.

8.0 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, which took approximately 40 to 45 minutes, is where the majority of the simulator sickness occurred due to the bouncy rocky terrain and the constant weaving to avoid craters. Additionally, researchers confirm that simulator sickness is cumulative over time with some individuals getting worst symptoms while other adapted.

The correlation analysis indicated the SAE-J1441 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-J1441 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 data (Table 27).

Table 27. *Apollo LRV Speeds [45,46,47] 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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APPENDIX A. TERRAIN CHAARACTERISTICS TABLES

Table A1. *Total Lunar Terrain Elements*

Elements	Total Number	Crater Depth Ratio (depth/diameter in meters)	Notes
Easter Egg Rocks	15		Specially placed rocks
Small Rocks	1,254,370		
Medium Rocks	229,122		
Young Craters	6,456	02. to 0.195	90% old craters and 10% new craters
Medium Young Craters	6,767	0.195 to 0.19	
Medium Old Craters	51,270	0.19 to 0.15	
Old Craters	64,106	0.15 to 0.1	

Table A2. *Artemis Base Camp Crater Characteristics*

Site	Lunar Location		Terrain Area Diameter (meters)	Craters	
	Lat	Long		Diameter Size	Number
ABC HAB	-89.45066	-137.2426	250	<1m	1169
				1 to 2m	1829
				2 to 3m	1233
				3 to 4m	738
				4 to 5m	468
				5 to 6m	337
				6 to 7m	220
				7 to 8m	139
				8 to 9m	70
				9 to 10m	72
				10m>	37

Table A3. *Artemis Base Camp Rock Characteristics*

Site	Lunar Location		Terrain Area Diameter (meters)	Rock/Boulder			
	Lat	Long		Rock Type	Description	Size (cm)	Density (#/m^2)
ABC HAB	-89.45066	-137.2426	250	Small	Medium to Large Pebbles	3.4 to 6.4	0.322
				Medium	Cobbles	6.4 to 25.6	0.034
				Large	Boulders	25.6 to 4.096 (meters)	0.02

Table A4. *Bear Paw Crater Characteristics*

Site	Lunar Location		Terrain Area Diameter (meters)	Craters	
	Lat	Long		Diameter Size	Number
Bear Paw	-85.6459	-153.4739	250	<1m	2078
				1 to 2m	2886
				2 to 3m	1976
				3 to 4m	1236
				4 to 5m	807
				5 to 6m	533
				6 to 7m	326
				7 to 8m	194
				8 to 9m	135
				9 to 10m	82
				10m>	27

Table A5. *Bear Paw Rock Characteristics*

Site	Lunar Location		Terrain Area Diameter (meters)	Rock/Boulder			
	Lat	Long		Rock Type	Description	Size (cm)	Density (#/m^2)
Bear Paw	-85.6459	-153.4739	250	Small	Medium to Large Pebbles	3.4 to 6.4	0.264
				Medium	Cobbles	6.4 to 25.6	0.044
				Large	Boulders	25.6 to 4.096 (meters)	0

APPENDIX B. DETAILED TEST TRACK PARAMETERS

HQ Mission Parameters for LTV

A.1 **Forward Driving and Braking- Straight on Smooth, Flat Surface**

A.1.1 **Objectives**

Ensure the handling qualities do not degrade while using X hand controller (Table 1.2)

Check of undesirable coupling of X hand controller (Table 1.2) while moving forward

A.1.2 **Cockpit Configuration**

Table A-1.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.1.3 **Description of Driving**

The typical role for a lunar rover generally requires traveling from one point to another via off-road lunar-country terrain on various surfaces. Starting at a predetermine point on a flat level surface, accelerate up to one of the specified speeds below in Table A-1.3 as soon as possible and hold that speed for 500 meters (depending on speed in Table A-1.3) distance while keeping the rover in a straightforward line. Perform the driving maneuver from the seat that best provides sufficient cueing of surface conditions. Note how fast vehicle stops at end of run to understand braking.

Table A-1.3. *Speeds for Forward Driving on Straight, Smooth, Flat Surface*

Speed (in kph)	Distance (in meters)	Terrain/Slope	Path Direction
8	500	Smooth/Level	Straight Forward
12	500	Smooth/Level	Straight Forward

A.1.4 **Description of Test Course**

Using a 1.44 km 3.66 m wide, flat, smooth, level lunar road-type surface (Figure A-1.4)

Figure A-1.4. *Proposed parameters for a straight flat, smooth lunar road-type surface.*

A.1.5 **Performance Standards**

Table A-1.5 *Forward Driving on Straight, Smooth, Flat Surface*

Performance Standards	Desired	Adequate	Failed
Maintain forward speed at X kph, +/- 1 kph	8 kph 12 kph	7 kph - 9 kph 11 kph - 13 kph	< 7 kph or > 9 kph < 11 kph or > 13 kph
Maintain a straight path of X meters, +/- 0.5 meters to the right or left of center line	0 variation from forward path center line	0.5 to -0.5 meters from forward path center line	> 0.5 m variation from forward path center line

A.1.6 **Timing Requirement**

Time for each task < 5 to 7 minutes

Total task time = 10 to 14 minutes

A.1	**Forward Driving and Braking- Straight on Smooth, Flat Surface**			
	Reconfiguration time for hand controller configuration approximately 5 minutes			
A.1.7	**Apollo Notes**			
	Apollo 15	**Apollo 16**	**Apollo 17**	**Notes**
	STRAIGHT LINE Velocity of the rover on level surface reached a maximum of 13 kph (8.1mph). General lunar terrain features were detectable within 10 degrees of the zero-phase region, but with constant attention, 10 to 11 kilometers (6.2 to 6.8 miles) per hour could be maintained. On the return from station 1 to station 2, rover tracks were used as directional aids and tacking out of the sun line allowed an increase in speed to approximately 10 kph (6.2 mph). Maneuvering was quite responsive at speed below approximately 5 kph (3.1 mph). **BRAKING** Straight line travel at approximately 10 kph (6.2 mph) on a level surface, vehicle could stop in a distance approximately twice the distance as the 1g trainer. Speeds under 5 kph (3.1 mph) braking appeared to occur in approximately the same distance as with the 1g trainer.	Poor. Down-sun speed was less than 5 kph (3.1 mph). Tacking out of sun line speed increased to ~10 kph (6.2mph).	The velocity of the rover on level surface reached a maximum of 13 kph (8.1 mph).	

HQ Mission Parameters for LTV

A.2 **Crater Field Driving**

A.2.1 **Objectives**

Ensure the handling qualities do not degrade while using X hand controller (Table 2.2) while driving through a representative crater field

Check of undesirable coupling of X hand controller (Table 2.2)while driving through a representative crater field

Understand areas of operator fatigue with X hand controller (Table 2.2) in X steering configuration (Table 2.3)

A.2.2 **Cockpit Configuration**

Table A-2.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.2.3 **Description of Driving**

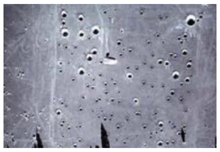
An important part of a vehicle's overall mobility performance capabilities is its ability to negotiate abrupt discreet obstacles without imposing excessive discomfort on the human operator or physical structure. Starting approximately 1000 meters from the entrance of the crater field, accelerate up to one of the specified speeds below in Table A-2.3 as soon as possible and hold that speed through the crater field , 400 meters (Table 2.3) while keeping the rover in a straightforward line. Perform the driving maneuver from the seat that best provides sufficient cueing of surface conditions.

Table A-2.3. *Speeds for Forward Crater Field Driving*

Speed (in kph)	Distance (in meters)	Terrain/Slope	Path Direction
5	400	Potholes/Level	Straight Forward

A.2.4 **Description of Test Course**

Using a rock field 400 meters in length by 100 meters in width. Crater diameters range from 1 to 2 meters with a depth of 0.2 to 0.15 meters. These are considered young to medium young craters.



Crater Field:
Length: 400 m
Width: 100m
Crater Size: Diameter = 1 to 2 m; Depth = 0. 2 to 0.15 m (Young to Medium Young Craters)

Figure A-2.4. *Proposed crater field for testing.*

A.2.5 **Performance Standards**

Table A-2.5 *Driving Over a Crater Field*

Performance Standards	Desired	Adequate	Failed
Maintain forward speed at X kph, +/- 0.5 kph	5 kph	4.5 kph - 5.5 kph	< 4.5 kph or > 5.5 kph
Maintain a straight path of X meters, +/- 5 meters to the right or left of center line	0 variation from path center line	5 to -5 meters from path center line	> 5 m variation from path center line

A.2.6 **Timing Requirement**

Time for each task 4 minutes

Total task time = 4 minutes

A.2	**Crater Field Driving**			
	Reconfiguration time for hand controller configuration approximately 5 minutes			
A.2.7	**Apollo Notes**			
	Apollo 15	**Apollo 16**	**Apollo 17**	**Notes**
	Obstacle avoidance was commensurate with speed. Lateral skidding occurred during any hard over or maximum rate turn above 5 kph (3.1 mph). A relatively straight-line traverse was easily maintained by selection of a point on the horizon despite maneuvering around smaller subdued craters. The small, hummocky craters were the major problem while negotiating the traverse. For obstacle avoidance, the optimum technique was to slow below 5 kph (3.1 mph) and then apply turning correction. In general, 1-meter (3.25 foot) craters were not detectable until the front wheels had approached to within 2 to 3 meters (6.5 to 10 feet).	Terrain while driving to station 1 on the first EVA was blocky and hummocky with many subdued-rim craters. Visibility was poor while driving to station in the zero-phase direction (down-sun) and was impossible to see far enough ahead to drive at maximum speed. Speed on outbound leg averaged less than 5 kph (3.1 mph). Visibility effect of zero-phase caused the rover to bounce through subdued craters (2 to 3 meters in diameter) (6.6 to 9.8 feet) that could not be seen. On second EVA, Survey Ridge terrain was so blocky and highly cratered that it was necessary to drive through the smaller secondary craters in order to avoid the larger steeper walled secondary craters. The vehicle ran in and out of the smaller craters	Double Ackermann steering greatly enhanced the maneuverability of the vehicle when negotiation craters and rocks.	

HQ Mission Parameters for LTV

A.2	**Crater Field Driving**			
		with ease. The suspension dynamics as the vehicle bounced out of a secondary crater resulted in the rover scraping a boulder which it normally would have cleared.		

A.3 Crater Rim Driving-Crabbing

A.3.1 Objectives

Ensure the handling qualities do not degrade while using X hand controller (Table 3.2)

Check of undesirable coupling of X hand controller (Table 3.2) while crabbing

A.3.2 Cockpit Configuration

Table A-3.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.3.3 Description of Driving

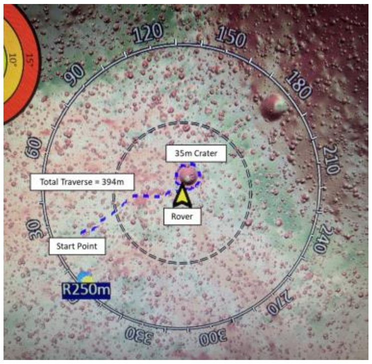
The typical role for a lunar rover generally requires traveling from one point to another via off-road lunar-country terrain on various surfaces. Starting at a predetermine point on a crater rim, put the front of the vehicle towards the crater and select crab mode. Start crabbing along the crater rim keeping the nose of the vehicle 1 meter from the rim and perpendicular to the crater while holding the specified speeds as shown in Table A3.3. Perform the driving maneuver from the seat that best provides sufficient cueing of surface conditions.

Table A-3.3. *Speeds for Driving on Crater Rim*

Speed (in kph)	Diameter of Crater (in meters)	Terrain/Slope	Path Direction
4	35	3º to 20º	Crabbing

A.3.4 Description of Test Course

Using a crater that is 35 m (114 feet) in diameter, maintain a 1-meter (3.28 feet) distance from the crater rim and perpendicular to the vehicle's nose (Figure A-3.4)



<u>Crater Rim:</u>
Diameter = 35 m
Distance = 394 m

Figure A-3.4. *Proposed parameters for crater rim maneuver.*

A.3.5 Performance Standards

Table A-3.5 *Driving a Crater Rim*

Performance Standards	Desired	Adequate	Failed
Maintain vehicle crab speed at X kph, +/- 1 kph	4 kph	3 kph - 5 kph	< 3 kph or > 5 kph
Maintain a nose to rim distance of X meters, +/- 0.5 meters	0 variation from rim	0.5 to -0.5 meters from rim	> 0.5 m variation from rim

A.3.6 Timing Requirement

Time for each task < 7 minutes

HQ Mission Parameters for LTV

<table>
<tr><td>A.3</td><td colspan="4">Crater Rim Driving-Crabbing</td></tr>
<tr><td rowspan="2"></td><td colspan="4">Total task time = 14 minutes</td></tr>
<tr><td colspan="4">Reconfiguration time for hand controller configuration approximately 5 minutes</td></tr>
<tr><td rowspan="3">A.3.7</td><td colspan="4">Apollo Notes</td></tr>
<tr><td>Apollo 15</td><td>Apollo 16</td><td>Apollo 17</td><td>Notes</td></tr>
<tr><td>na</td><td>na</td><td>na</td><td></td></tr>
</table>

A.4 **Slope Driving (UP/Down/Cross)**

A.4.1 **Objectives**

Ensure the handling qualities do not degrade while using X hand controller (Table 4.2)

Check of undesirable coupling of X hand controller (Table 4.2) while moving forward on various slopes

A.4.2 **Cockpit Configuration**

Table A-4.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.4.3 **Description of Driving**

The typical role for a lunar rover generally requires traveling from one point to another via off-road lunar-country terrain on various surfaces. Starting at a predetermine point on a flat level surface, accelerate up to one of the specified slopes below in Table A-4.3 holding a specific shown in Table 4.3 speed for 200-meter distance while keeping the rover in a straightforward line. Perform the driving maneuver from the seat that best provides sufficient cueing of surface conditions.

Table A-4.3. *Speeds for Forward Driving on a Sloped Surface*

Speed (in kph)	Distance (in meters)	Terrain/Slope	Path Direction
5	200	Craters with 20-degree Slope	Down Slope
8	200	Craters with 20-degree Slope	Cross Slope
10	200	Craters with 20-degree Slope	Up Slope

A.4.4 **Description of Test Course**

Using a X degree slope at a 30% grade with a length of 200 m (Figure A-5.4)

Slopes:
Slope Angle = 20 degrees
Slope Grade = 30%
Slope Length = 200 m

Figure A-4.4. *Proposed parameters for a slope at a 30%* grade

A.4.5 **Performance Standards**

Table A-4.5 *Forward Driving on Straight, Smooth, Flat Surface*

Performance Standards	Desired	Adequate	Failed
Maintain forward speed at X kph, +/- 1 kph	5 kph (Down Slope) 8 kph (Cross Slope) 10 kph (Up Slope)	4 kph - 6 kph 7 kph - 9 kph 9 kph - 11 kph	< 4 kph or > 6 kph < 7 kph or > 9 kph < 9 kph or > 11 kph
Maintain a straight path of X meters, +/- 0.5 meters to the right or left of center line	0 variation from forward path center line	0.5 to -0.5 meters from forward path center line	> 0.5 m variation from forward path center line

HQ Mission Parameters for LTV

<table>
<tr><td>A.4</td><td colspan="4">Slope Driving (UP/Down/Cross)</td></tr>
<tr><td rowspan="4">A.4.6</td><td colspan="4">Timing Requirement</td></tr>
<tr><td colspan="4">Time for each task < 4 minutes</td></tr>
<tr><td colspan="4">Total task time = 12 minutes</td></tr>
<tr><td colspan="4">Reconfiguration time for hand controller configuration approximately 5 minutes</td></tr>
<tr><td rowspan="3">A.4.7</td><td colspan="4">Apollo Notes</td></tr>
<tr><td>Apollo 15</td><td>Apollo 16</td><td>Apollo 17</td><td>Notes</td></tr>
<tr><td>Driving directly upslope on the soft surface material, maximum velocities of 10 kph (6.2 mph) were maintained. Comparable velocities could be maintained obliquely on slopes with the downhill wheel tended to dig in and the speed was reduced for safety.
Traction of the wheels was excellent uphill, downhill, and during acceleration. A top speed of 10 kph (6.2 mph) could be attained in approximately 3 vehicle lengths was very will wheel slip.</td><td>Slope up to 7 to 8 degrees were negotiated.
At Stone Mountain, the vehicle 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.
The best way to negotiate slopes in the rover is to go straight up and straight down.
Going cross-slope or parallel to contour lines produces right or left rolls of 10 to 15 degrees. The feeling is very uncomfortable, even though the vehicle was never unstable during cross-slope driving.</td><td>Slopes of up to 20 degrees were easily negotiated in a straight-ahead mode. While climbing such slopes at full power, the vehicle decelerated to a constant speed of 4 to 5 kilometer per hour (2.5 to 3.1 mph). Driving up-slope on soft surface material at the Apennine Front maximum velocities on 10 kph (6.2 mph) were maintained.
Coming down these slopes, the vehicle was operated in a braking mode with no indication of brake-fading or feeling that the rover was uncontrolled.
Side slopes were negotiable, but not necessarily comfortable and engendered a great deal more caution. Although the crew believed the rover could have negotiated slopes of 20 to 25 degrees without great difficulty, side slope operations never became comfortable.
Comparable velocities could be maintained obliquely on the slopes unless crater avoidance became necessary.</td><td></td></tr>
</table>

A.5 **Inspection Driving (360 Around a Point) (Ackermann Steering ONLY)**

A.5.1 **Objectives**

Ensure the handling qualities do not degrade while using X hand controller (Table 5.2)

Check of undesirable coupling of X hand controller (Table 5.2) while turning

A.5.2 **Cockpit Configuration**

Table A-5.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.5.3 **Description of Driving**

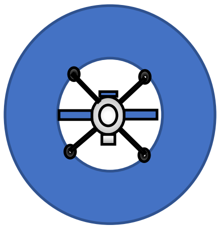
The typical role for a lunar rover generally requires traveling from one point to another via off-road lunar-country terrain on various surfaces. Starting at a predetermine point on a flat level surface, move the vehicle up to 5 meters to the item being inspected. Started turning the vehicle around the item without using crab mode and maintain 5-meter distance from the inspection item to the nose of the vehicle. Perform the driving maneuver from the seat that best provides sufficient cueing of surface conditions.

Table A-5.3. *Speeds for Forward Driving on Straight, Smooth, Flat Surface*

Speed (in kph)	Distance (in meters)	Terrain/Slope	Path Direction
3	5	Smooth/Level	Turning

A.5.4 **Description of Test Course**

Example inspection item could the lunar lander and using a circle turn radius of 5 m (Figure A-5.4)



Boulder:
Height = 50m
Diameter = 15 m
Circle Path:
Diameter = 1.5 m

Figure A-5.4. *Proposed parameters for a 360 degree turn around a point maneuver*

A.5.5 **Performance Standards**

Table A-5.5 *360 Degree Turn Around a Point Maneuver*

Performance Standards	Desired	Adequate	Failed
Maintain turning speed at X kph, +/- 1.0 kph	3 kph	2 kph - 4 kph	< 2 kph or > 4 kph
Maintain a turning path of 5 meters, +/- 1.0 meters of the item being inspected	0 variation from turning path to item being inspected	1.0 to -1.0 meters from turning path to item being inspected	> 1.0 m variation from turning path to item being inspected

A.5.6 **Timing Requirement**

Time for each task < 5 minutes

Total task time = 10 minutes

Reconfiguration time for hand controller configuration approximately 5 minutes

A.5.7 **Apollo Notes**

A.5	**Inspection Driving (360 Around a Point) (Ackermann Steering ONLY)**			
	Apollo 15	**Apollo 16**	**Apollo 17**	**Notes**
	na	na	na	

A.6 **Long Traverse-Various Terrain**

A.6.1 **Objectives**

Ensure the handling qualities do not degrade while using X hand controller (Table 6.2)

Check of undesirable coupling of X hand controller (Table 6.2) during a long nominal traverse over various terrain

A.6.2 **Cockpit Configuration**

Table A-6.2. *Hand Controller Configurations*

Hand Controller	Configuration	Notes
SEV Joystick	Single	

A.6.3 **Description of Driving**

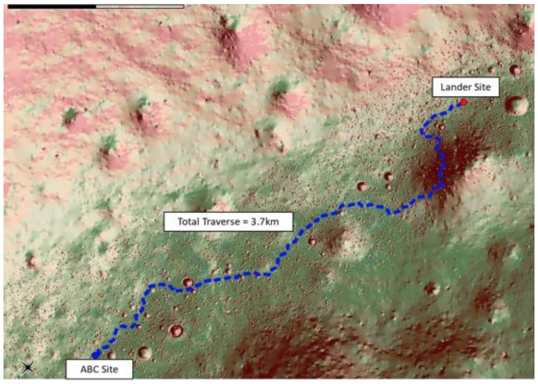
The typical role for a lunar rover generally requires traveling from one point to another via off-road lunar-country terrain on various surfaces. Starting at a predetermine point on a flat level surface, acceleration will vary when terrain features and/or different lighting conditions are encounter. Perform all driving maneuvers from the seat that best provides sufficient cueing of surface conditions.

Table A-6.3. *Speeds for Long Duration Traverse*

Speed (in kph)	Distance (in kilometers)	Terrain/Slope	Path Direction
Variable	5.0	Various	Follow XI Blue Traverse Path and avoid terrain features

A.6.4 **Description of Test Course**

Using a 5.0 km (3.12 miles) nominal south pole lunar terrain surface (Figure A-6.4)



Long Traverse Path:
Length 5.0 (km)

Figure A-6.4. *Long Traverse under nominal South Pole lunar lighting and terrain conditions*

A.6.5 **Performance Standards**

Table A-6.5 L*ong Traverse Driving Parameters*

Performance Standards	Desired	Adequate	Failed
Maintain forward speed at X kph, +/- 1 kph	8 to 12 kph	7 kph - 9 kph 11 kph - 13 kph	< 7 kph or > 9 kph < 11 kph or > 13 kph
Maintain on Blue Traverse Path of X meters, +/- 10 meters to the right or left of center line	0 variation from forward path center line	10 to -10 meters from forward path center line	>10 m variation from forward path center line

A.6	**Long Traverse-Various Terrain**			
A.6.6	**Timing Requirement**			
	Time for each task < 40 minutes			
	Total task time = 40 minutes			
	Reconfiguration time for hand controller configuration approximately 5 minutes			
A.6.7	**Apollo Notes**			
	Apollo 15	**Apollo 16**	**Apollo 17**	**Notes**
	Velocity of the rover on level surface reached a maximum of 13 kph (8.1mph). General lunar terrain features were detectable within 10 degrees of the zero-phase region, but with constant attention, 10 to 11 kilometers (6.2 to 6.8 miles) per hour could be maintained. On the return from station 1 to station 2, rover tracks were used as directional aids and tacking out of the sun line allowed an increase in speed to approximately 10 kph (6.2 mph). Maneuvering was quite responsive at speed below approximately 5 kph (3.1 mph).	Poor. Down-sun speed was less than 5 kph (3.1 mph). Tacking out of sun line speed increased to ~10 kph (6.2mph).	The velocity of the rover on level surface reached a maximum of 13 kph (8.1 mph).	

APPENDIX C. SPEARMAN CORRELATIONS TABLE

Correlations

			BWS	CHR	SAECR	SAEDIST	CRAbThmp	CRSmthHrsh	CRAccInacc	CRInterUninv	CRRespUnresp	CRFriskSlug	CRQuickSlow	CRSpeedLeisur	CRAdhesSlippy	CRGrippySkiddy	CRFirmBouncy	CRNoRollTendToLean	CRPoisedNervy	CRNoOverstrTailoverstr	CRNounderstNoseploughfwd	CRControlledUncontrolled	CRSolidLoose	CRStableUnstable
Spearman's rho	BWS	Correlation Coefficient	1.000	.749**	.503**	.502**	.432**	.469**	.346**	.180	.221*	-.009	.101	.053	.282**	.223*	.284**	.166	.396**	.321**	.131	.383**	.294**	.344**
		Sig. (2-tailed)	.	.000	.000	.000	.000	.000	.000	.067	.024	.932	.310	.597	.004	.023	.003	.093	.000	.001	.185	.000	.002	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CHR	Correlation Coefficient	.749**	1.000	.559**	.491**	.389**	.389**	.380**	.229*	.270**	.068	.169	.094	.293**	.256**	.319**	.146	.384**	.383**	.159	.470**	.298**	.351**
		Sig. (2-tailed)	.000	.	.000	.000	.000	.000	.000	.020	.006	.496	.086	.340	.003	.009	.001	.140	.000	.000	.106	.000	.002	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	SAECR	Correlation Coefficient	.503**	.559**	1.000	.642**	.343**	.329**	.670**	.444**	.492**	.227*	.343**	.271**	.349**	.363**	.375**	.347**	.506**	.351**	.299**	.581**	.473**	.552**
		Sig. (2-tailed)	.000	.000	.	.000	.000	.001	.000	.000	.000	.020	.000	.005	.000	.000	.000	.000	.000	.000	.002	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	SAEDIST	Correlation Coefficient	.502**	.491**	.642**	1.000	.440**	.417**	.549**	.388**	.489**	.279**	.348**	.329**	.390**	.323**	.397**	.270**	.505**	.313**	.264**	.511**	.426**	.501**
		Sig. (2-tailed)	.000	.000	.000	.	.000	.000	.000	.000	.000	.004	.000	.001	.000	.001	.000	.006	.000	.001	.007	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRAbThmp	Correlation Coefficient	.432**	.389**	.343**	.440**	1.000	.854**	.326**	.217*	.203*	.159	.172	.161	.304**	.349**	.463**	.063	.451**	.333**	.199*	.421**	.283**	.352**
		Sig. (2-tailed)	.000	.000	.000	.000	.	.000	.001	.027	.039	.107	.081	.103	.002	.000	.000	.526	.000	.001	.043	.000	.004	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRSmthHrsh	Correlation Coefficient	.469**	.389**	.329**	.417**	.854**	1.000	.305**	.176	.197*	.084	.085	.100	.346**	.412**	.457**	-.030	.343**	.365**	.182	.424**	.268**	.403**
		Sig. (2-tailed)	.000	.000	.001	.000	.000	.	.002	.074	.045	.396	.394	.311	.000	.000	.000	.763	.000	.000	.064	.000	.006	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRAccInacc	Correlation Coefficient	.346**	.380**	.670**	.549**	.326**	.305**	1.000	.643**	.600**	.318**	.433**	.390**	.411**	.403**	.383**	.277**	.408**	.335**	.413**	.627**	.523**	.536**
		Sig. (2-tailed)	.000	.000	.000	.000	.001	.002	.	.000	.000	.001	.000	.000	.000	.000	.000	.004	.000	.001	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRInterUninv	Correlation Coefficient	.180	.229*	.444**	.388**	.217*	.176	.643**	1.000	.592**	.361**	.560**	.506**	.394**	.339**	.329**	.496**	.434**	.314**	.490**	.463**	.419**	.502**
		Sig. (2-tailed)	.067	.020	.000	.000	.027	.074	.000	.	.000	.000	.000	.000	.000	.000	.001	.000	.000	.001	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRRespUnresp	Correlation Coefficient	.221*	.270**	.492**	.489**	.203*	.197*	.600**	.592**	1.000	.467**	.535**	.455**	.440**	.427**	.414**	.419**	.427**	.397**	.468**	.538**	.543**	.554**
		Sig. (2-tailed)	.024	.006	.000	.000	.039	.045	.000	.000	.	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRFriskSlug	Correlation Coefficient	-.009	.068	.227*	.279**	.159	.084	.318**	.361**	.467**	1.000	.789**	.811**	.486**	.516**	.349**	.342**	.322**	.243*	.489**	.349**	.434**	.384**
		Sig. (2-tailed)	.932	.496	.020	.004	.107	.396	.001	.000	.000	.	.000	.000	.000	.000	.000	.000	.001	.013	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRQuickSlow	Correlation Coefficient	.101	.169	.343**	.348**	.172	.085	.433**	.560**	.535**	.789**	1.000	.898**	.542**	.526**	.439**	.425**	.508**	.287**	.535**	.432**	.625**	.522**
		Sig. (2-tailed)	.310	.086	.000	.000	.081	.394	.000	.000	.000	.000	.	.000	.000	.000	.000	.000	.000	.003	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRSpeedLeisur	Correlation Coefficient	.053	.094	.271**	.329**	.161	.100	.390**	.506**	.455**	.811**	.898**	1.000	.530**	.539**	.464**	.406**	.436**	.265**	.483**	.368**	.548**	.459**
		Sig. (2-tailed)	.597	.340	.005	.001	.103	.311	.000	.000	.000	.000	.000	.	.000	.000	.000	.000	.000	.007	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRAdhesSlippy	Correlation Coefficient	.282**	.293**	.349**	.390**	.304**	.346**	.411**	.394**	.440**	.486**	.542**	.530**	1.000	.828**	.687**	.361**	.562**	.579**	.559**	.619**	.678**	.634**
		Sig. (2-tailed)	.004	.003	.000	.000	.002	.000	.000	.000	.000	.000	.000	.000	.	.000	.000	.000	.000	.000	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRGrippySkiddy	Correlation Coefficient	.223*	.256**	.363**	.323**	.349**	.412**	.403**	.339**	.427**	.516**	.526**	.539**	.828**	1.000	.679**	.296**	.459**	.556**	.497**	.571**	.637**	.599**
		Sig. (2-tailed)	.023	.009	.000	.001	.000	.000	.000	.000	.000	.000	.000	.000	.000	.	.000	.002	.000	.000	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRFirmBouncy	Correlation Coefficient	.284**	.319**	.375**	.397**	.463**	.457**	.383**	.329**	.414**	.349**	.439**	.464**	.687**	.679**	1.000	.369**	.538**	.527**	.509**	.630**	.587**	.590**
		Sig. (2-tailed)	.003	.001	.000	.000	.000	.000	.000	.001	.000	.000	.000	.000	.000	.000	.	.000	.000	.000	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRNoRollTendToLean	Correlation Coefficient	.166	.146	.347**	.270**	.063	-.030	.277**	.496**	.419**	.342**	.425**	.406**	.361**	.296**	.369**	1.000	.583**	.297**	.354**	.368**	.425**	.412**
		Sig. (2-tailed)	.093	.140	.000	.006	.526	.763	.004	.000	.000	.000	.000	.000	.000	.002	.000	.	.000	.002	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRPoisedNervy	Correlation Coefficient	.396**	.384**	.506**	.505**	.451**	.343**	.408**	.434**	.427**	.322**	.508**	.436**	.562**	.459**	.538**	.583**	1.000	.480**	.454**	.605**	.593**	.606**
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.001	.000	.000	.000	.000	.000	.000	.	.000	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRNoOverstrTailoverstr	Correlation Coefficient	.321**	.383**	.351**	.313**	.333**	.365**	.335**	.314**	.397**	.243*	.287**	.265**	.579**	.556**	.527**	.297**	.480**	1.000	.567**	.676**	.483**	.551**
		Sig. (2-tailed)	.001	.000	.000	.001	.001	.000	.001	.001	.000	.013	.003	.007	.000	.000	.000	.002	.000	.	.000	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRNounderstNoseploughfwd	Correlation Coefficient	.131	.159	.299**	.264**	.199*	.182	.413**	.490**	.468**	.489**	.535**	.483**	.559**	.497**	.509**	.354**	.454**	.567**	1.000	.523**	.603**	.481**
		Sig. (2-tailed)	.185	.106	.002	.007	.043	.064	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.	.000	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRControlledUncontrolled	Correlation Coefficient	.383**	.470**	.581**	.511**	.421**	.424**	.627**	.463**	.538**	.349**	.432**	.368**	.619**	.571**	.630**	.368**	.605**	.676**	.523**	1.000	.668**	.768**
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.	.000	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRSolidLoose	Correlation Coefficient	.294**	.298**	.473**	.426**	.283**	.268**	.523**	.419**	.543**	.434**	.625**	.548**	.678**	.637**	.587**	.425**	.593**	.483**	.603**	.668**	1.000	.816**
		Sig. (2-tailed)	.002	.002	.000	.000	.004	.006	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.	.000
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104
	CRStableUnstable	Correlation Coefficient	.344**	.351**	.552**	.501**	.352**	.403**	.536**	.502**	.554**	.384**	.522**	.459**	.634**	.599**	.590**	.412**	.606**	.551**	.481**	.768**	.816**	1.000
		Sig. (2-tailed)	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.
		N	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104	104