NASA/TM-20240001217

Lunar Terrain Vehicle (LTV) Remote Teleoperation Studies Under Four Lunar Communication Latencies

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January 2024

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CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACRONYMS

.cvs	Excel codex
º	degree
<	less than
%	percentage
ABC	Artemis Base Camp
ACES	Academy Color Encoding System
ANOVA	Analysis of Variance
CEL	Concept Exploration Laboratory
cm	centimeters
conops	Concept of Operations
deg	degree
DEM	Digital Environment Model
DOUG	Dynamic Onboard Ubiquitous Graphics
DRATS	Desert Research and Technology Studies
DSN	Deep Space Network
DTE	Direct to Earth
EDGE	Graphics for Exploration
EHP	NASA's Extravehicular Activity and Human Surface Mobility Program
ESDMD	Exploration Systems Development Mission Directorate
EVA	ExtraVehicular Activity
F	ANOVA *F* value
FOD	Foreign Object Debris
FOV	Field-of-View
fps	frames per second
GUNNS	General-Use Nodal Network Solver software
HAB	Habitat
HDR	High Data Rate
HITL	Human-in-the-Loop
hh:mm:ss	hours, minutes, seconds
IES	Illuminating Engineering Society
IMU	Inertial Measurement Unit
ISRU	In-Situ Resource Utilization Unit
JEOD	Johnson Space Center Engineering Orbital Dynamics Group
JSC	Johnson Space Center
kg	kilogram
km	kilometers
kph	kilometers per hour
kW	kilo Watts
kW-h	kilo Watts per hour
LIDAR	Light Intensification Detection and Ranging

ACRONYMS

LDR	Low Data Rate
LRO	Lunar Reconnaissance Orbiter
LRV	Apollo Lunar Roving Vehicle
LTV	NASA's Lunar Terrain Vehicle
lux	a unit of illumination
m	meter
M	Mean
m^3	cubic meters
Mbdyn	MultiBody Dynamics software
MCC	Mission Control Center
MRV	Modular Robotic Vehicle
NASA	National Aeronautics and Space Administration
OLED	Organic Light Emitting Diode
p	alpha value
PR	NASA's Pressurized Rover
PTZ	Pan/Tilt/Zoom
s	seconds
SAO	Strategy and Architecture Office
SD	Standard Deviation
SE&I	System Engineering and Integration
SEAL	The Simulation and Exploration Analysis Lab
SES	Systems Engineering Simulators
SRD	System Requirements Document
t	Pairwise t-Test
TLX	NASA's Task Load Index
VR	Virtual Reality
XI	JSC Astromaterials Research and Exploration Science Division

EXECUTIVE SUMMARY

Remotely operating a lunar rover from Earth while subject to an Earth-Moon time delay of multiple seconds could result in a dangerous state where the roving vehicle is either damaged or lost, thereby potentially compromising an entire mission or series of missions. Providing the right capabilities to the remote operator to manage inherent communication latencies will be important for remote driving to be successful.

NASA conducted two studies to investigate the average speed and number of kilometers per day that an operator on Earth could teleoperate a notional Artemis unpressurized rover with minimal remote operator capabilities under 0- and 4-second communication delays (April 2023 study) and 6- and 8-second delays (August 2023 study). A primary goal of these studies was to understand if an Artemis Lunar Terrain Vehicle (LTV) could cover 6 kilometers (km) in 24 hours when operated remotely. During the April 2023 evaluation, eight test operators used an in-house simulation of the lunar surface South Pole to teleoperate a NASA government reference LTV. Each operator received approximately 30 minutes of remote driving familiarization/training prior to their test run. Operators viewed the surrounding terrain via a single, rover mast-mounted, high-resolution camera with pan/tilt/zoom capabilities; continuous communication was provided throughout all testing. In the August 2023 evaluation, remote operators received approximately 3 hours of familiarization training in each latency, and the simulation environment provided remote operators with an operator-selected rate limiter to enable finer sensitivity in the hand controller and a predictive circle function to better assist operators with predicting the path the vehicle could take. All test operators were able to successfully navigate and drive through six different types of terrain and five planned traverse scenarios using natural lighting under all communication delays. Results for average speeds for each communication delay, computed by averaging the data from all test conditions for that latency and all operators, are shown in the table below. The average speed data was then used to derive the total time needed to cover 6 km, 8 km, and 20 km (distances relevant to LTV-SYS-071 and -029 requirements).

Average Speeds for Remote Operations of the Lunar Terrain Vehicle For Four Communication Delays. These average speeds were then used to derive the amount of time needed to cover 6, 8, and 20 km (distances relevant to LTV-SYS-071 and -029 requirements)

Communication Delay	**Average Speed (kph) across all test conditions**	**Distance (km)**	**Time (hh:mm:ss)**
0-Second Latency	3.24	6 [a]	1:51:07
		8 [a]	2:28:09
		20 [b]	6:10:22
4-Second Latency	2.56	6	2:20:38
		8	3:07:30
		20	7:48:45
6-Second Latency	2.03	6	2:57:20
		8	3:56:27
		20	9:51:08
8-Second Latency	1.76	6	3:24:33
		8	4:32:44
		20	11:21:49

Note[a]: LTV-SYS-071 6km (threshold), 8km (goal) distance in one 24-hour period when operated remotely

Note[b]: LTV-SYS-029 no less than 20km without stopping for recharge

Remote operators drove slower and used the brake more frequently when subject to a communication latency as opposed to no communication latency. Subjective workload assessments revealed that while operating in a latency the overall workload significantly increased when compared to a 0-s delay with mental demand, frustration, and performance being the primary contributing factors. Driving strategies in the 0-s delay did not vary significantly among subjects; however, in the 4-s delay condition, three different driving strategies were identified. In the 6-s and 8-s latency conditions the operator's use of the cruise control to maintain speed was more apparent. Additionally, over the course of the August study, the operator took advantage of the predictive circle indicator on the navigation display and over 95% of the operator's navigation used the mast camera 180-degree panning function for ground truthing in terms of boulders and craters. Operators started to define more specific parameters in driving strategies for general operations. This consisted of setting the vehicle into a low-speed cruise mode of approximately 1–1.5 kph and noticing driving performance of the vehicle seemed to be much harder at slower speeds 0.4–0.8 kph; however, the vehicle was more responsive at speeds of 2.9–3.6 kph. Regardless of communication delay, operators used both the horizontal translation rails and the vehicle fenders as guides to predict a path for the vehicle through heavily concentrated terrain features.

Test operators acknowledged that the teleoperations training for this study was substantially less than what an actual LTV remote operator will ultimately receive. They estimated a minimum of 20 to 100 hours spread across multiple days and weeks (e.g., strategies included immersion training over a 3-day period, to a short 8-week starter program) would be needed to get an operator ~ 60% proficient (i.e., able to complete a subset of remote driving tasks), to a yearlong program for full proficiency in remote driving tasks under all terrain types and natural lighting conditions.

Remotely operating a vehicle on another planetary body while subject to communication latency is a complex task. Speed, distance covered, time spent driving, time spent navigating, brake usage and rock contacts are all affected by operator workload, driving strategies, workstation ergonomics and training. These studies provided a "first-look" answer to a potential system requirement (namely if a remote operator could cover a given distance in a given amount of time); however, considerable general knowledge was gained to begin to understand what it will take to make a successful lunar rover teleoperator.

1.0 INTRODUCTION

The Apollo Lunar Roving Vehicle (LRV) flew on Apollo 15, 16 and 17 lunar missions (Figure 1). The Artemis unpressurized LTV will build upon the Apollo LRV but be subject to unique challenges with respect to the new exploration region of the Lunar South Pole. The LTV will also need to interface with a new spacesuit, support new science objectives, and be reusable – namely be able to support 10 years of crewed and uncrewed mission operations [1]. The vehicle will have the ability to survive eclipse period and extended periods of continuous shadow. It will be able to be remotely operated from Earth, including traversing between waypoints of interest and interfacing with science instruments and payloads. A notional government reference LTV that was used in this study is depicted in Figure 2.

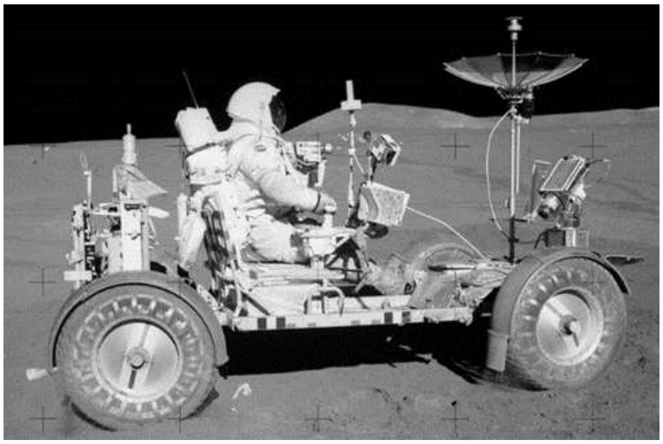


Figure 1.The Apollo LRV on the Moon.

Figure 2. A notional government reference LTV, which was used in this study

2.0 STUDY OBJECTIVES AND OUTCOME PRODUCTS

The objective of these studies was to determine the kilometers (km) per day an operator on Earth could remotely drive a notional LTV with minimal remote operator capabilities under four communication delays: 0-s, 4-s, 6-s, and 8-s roundtrip (Earth-Moon-Earth) delay. The LTV remote operations capabilities included a single high-definition camera view with pan/tilt/zoom capabilities. The HD camera had a field-of-view (FOV) of 2.2 to 58.5-degrees horizontal and 1.2 to 34-degrees vertical and a 1920 x 1080 at 60 frames per second (fps) resolution. The remote-control operator console included two displays to show camera view and navigation information and a joystick hand controller to provide translation inputs to the rover. Testing utilized a notional government reference LTV with associated rover performance and terramechanics models. A secondary objective was to collect exploratory data on workload while under a 0-s, 4-s, 6-s, and 8-s communications delay.

The purpose of these studies was to understand the average speed (and hence derive an approximate number of km per day) that a remote operator could safely and successfully teleoperate the rover. The requirements being investigated are from the Lunar Terrain Vehicle (LTV) System Requirements Document (SRD):

- LTV-SYS-071 (Uncrewed Daily Range) which states: *The vehicle shall be able to traverse 6 km (threshold), 8 km (goal) in one 24-hour period when operated remotely* [23].

- LTV-SYS-029 (Vehicle Range) which states: "*Vehicle shall have a range of no less than 20 km without stopping for a recharge while at full performance*." [23] This is based on light shadow data using a traverse from Connect Ridge to de Gerlache crater.

3.0 STUDY ASSUMPTIONS, CONSTRAINTS AND LIMITATIONS

Testing assumed continuous high-bandwidth communication between the LTV and the remote operator. No time constraints were imposed on the test operators when they conducted the remote driving. Unlike the eventual flight LTV, autonomous hazard detection by the LTV was not incorporated in the simulation. The remote operations console was not necessarily flight-like. Additionally, not much physical effort was required to use the joystick and the test operator was not in the simulation long enough to experience potential fatigue from utilizing the hand controller (although operators did comment that the ergonomics of the workstation were not ideal). Test operators also received a limited amount of familiarization training, on the order of approximately 15 minutes (April study) to 3 hours (August study) for each communication latency test condition, which was far less than what an actual LTV remote operator will receive in the future.

4.0 TESTING FACILITIES AND SIMULATIONS

4.1 The Simulation and Exploration Analysis Lab (SEAL)

For the April Study, all testing was conducted in the National Aeronautics and Space Administration (NASA) Johnson Space Center's (JSC) Simulation and Exploration Analysis Lab (SEAL). The SEAL housed two fully redundant remote operator workstations, as well as a simulation station for testing (Figure 3). Each workstation consisted of two 15-inch computer monitors and an LTV joystick hand controller. During testing the left monitor depicted a notional navigation and vehicle systems information screen, while the right monitor displayed the remote operations camera view from the rover on the lunar surface (Figure 4).

Figure 3. The Simulation and Exploration Analysis Lab (SEAL).

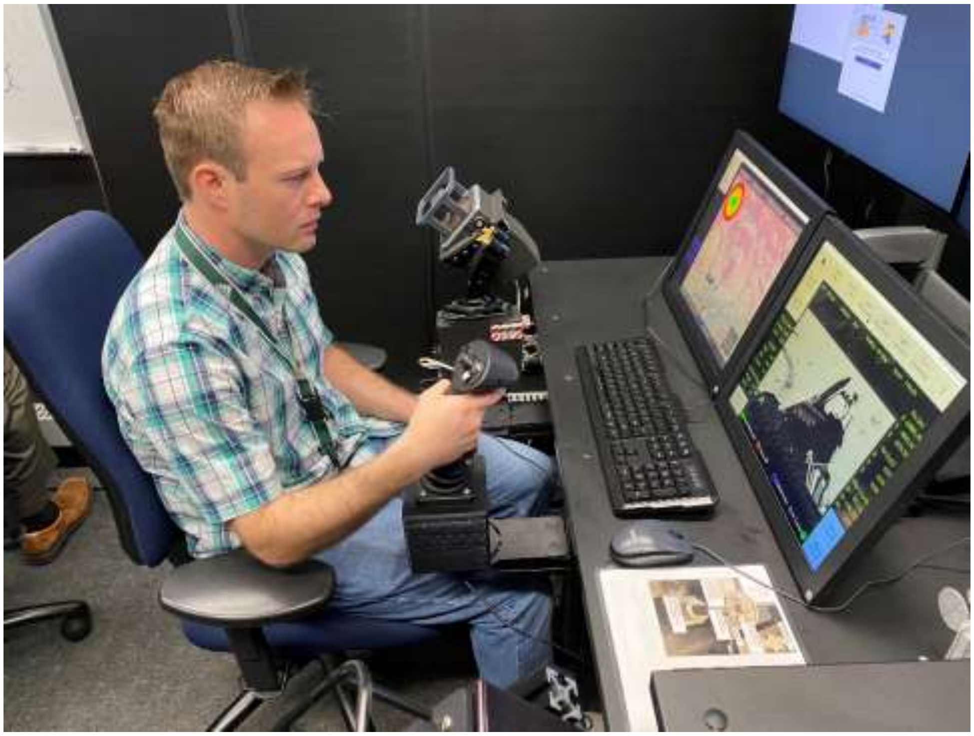


Figure 4. The SEAL workstations.

During the August study, testing took place in a simulated mission control center located on the second floor of Building 16 at JSC in the Systems Engineering Simulators (SES) facility at the Concept Exploration Laboratory (CEL) (Figure 5).There are six consoles positions and one flight director and sim sup console with computers, monitors, and communications (Figure 6). The far wall from the entrance has a large white screen and a projector so all controllers can see video feeds from the lunar surface. The room can be reconfigured to meet the demands of what the test team will need. The functional mapping of the hand controller is described in Table 1 and Figure 7.

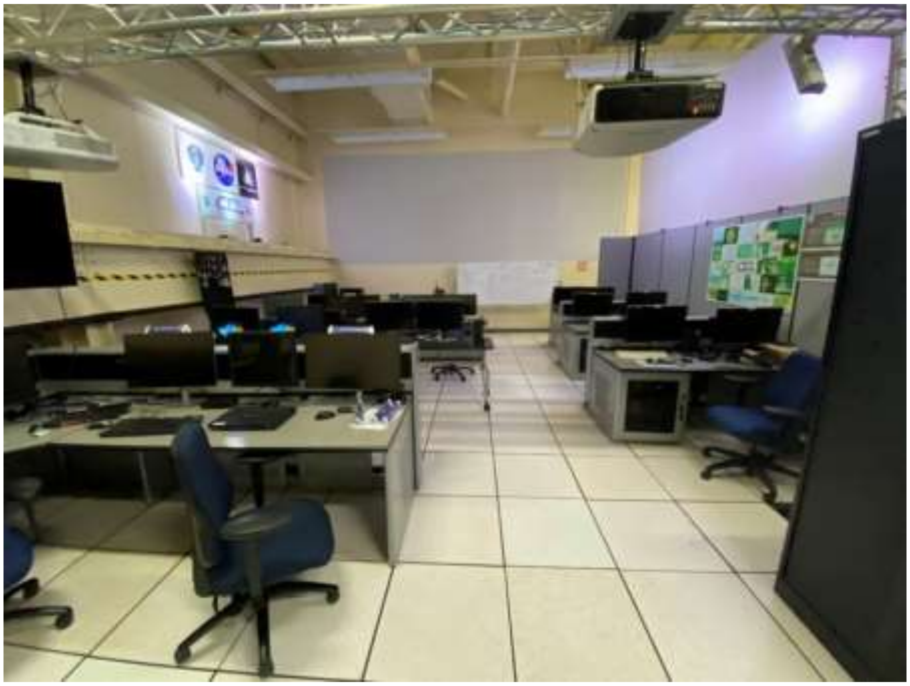


Figure 5. The simulated mission control room located in the CEL.

Figure 6. The Mission Control Center (MCC) team working at the consoles in the CEL.

Table 1. *The Pressurized Rover (PR) Joystick Functional Mapping*

	Controller Direction	Controller Motion	Vehicle Response
LTV 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 90º)
	Lean Left	Push/Lean Controller to the Left	Vehicle goes sideways to the left (wheels at 90º)
	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 (see Figure 5)
	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	Trigger center of grip below Controller Head	Momentary Break (Not Shown in Figure)

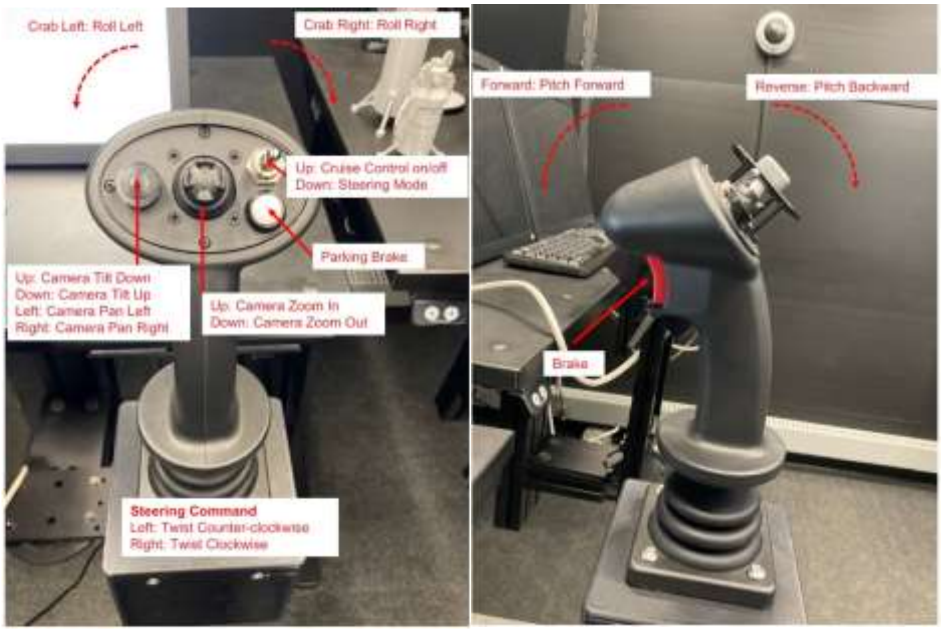


Figure 7. The LTV remote operator joystick hand controller functional mapping that will be used for testing.

4.2 Simulated LTV

The notional government reference LTV modeled in the simulation could traverse forward and backwards, had a turning radius of 0° (i.e., can turn in place), was able to crab (i.e., move perpendicular to the direction the nose is pointing), could travel at speeds up to 12 kph, and could traverse slopes of +/- 20º (up-, down-, cross-slope) (Figure 8).

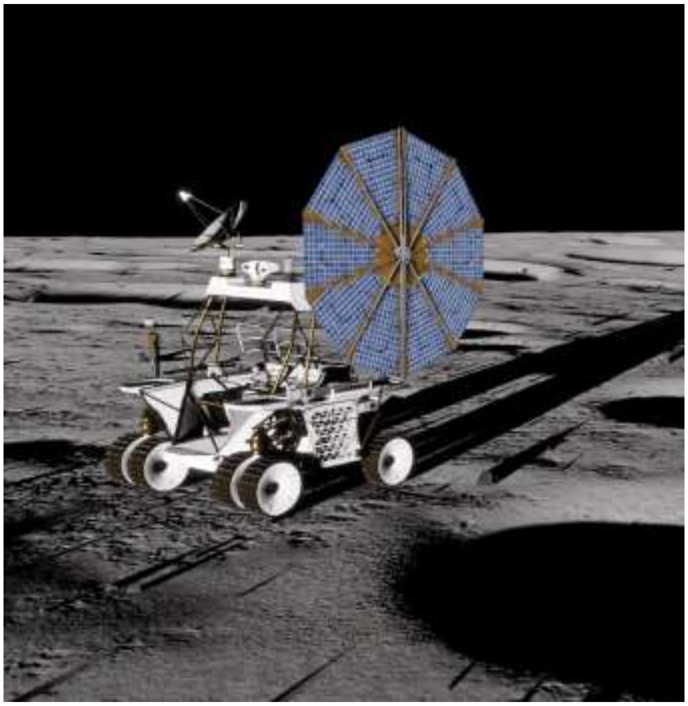
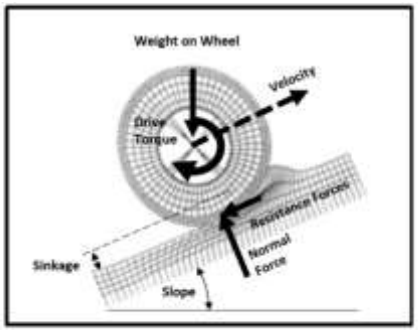


Figure 8. The virtual LTV Option 4.

The simulation consists of a multi-body dynamic model developed using MultiBody Dynamics (MBdyn) software and the Johnson Space Center Engineering Orbital Dynamics (JEOD) [21] group, a representative electrical power system model developed using the General-Use Nodal Network Solver (GUNNS) software [22], rock contact model developed using Pong, and a simple terramechanics model. The multi-body dynamics model consists of individual dynamic models for rover chassis, suspensions, and wheels. These dynamic models are integrated with the contact modelling package (Pong) to determines the normal force and tractional force on each wheel. The representative electrical power system model consists of models for solar array, solar array regulator, batteries, constant power load for rover hotel load, and motor-gearing modules for propulsion and steering. 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 (Figure 9). The terramechanics model are currently in validation phase, which will be a useful model in future engineering analysis. These models are integrated together to simulate the driving dynamics and power consumption of the rover during traverse. In addition, the virtual vehicle has a full lighting and camera array (Figure 10 and Figure 11). In this study, only a single camera view was used. The Mast Camera on the LTV located in the center of the accessory bar, is the Axis Communications Q6215-LE (Figure 12). Specifications for the camera which has been inputted into the simulation can be seen in Table 2.



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

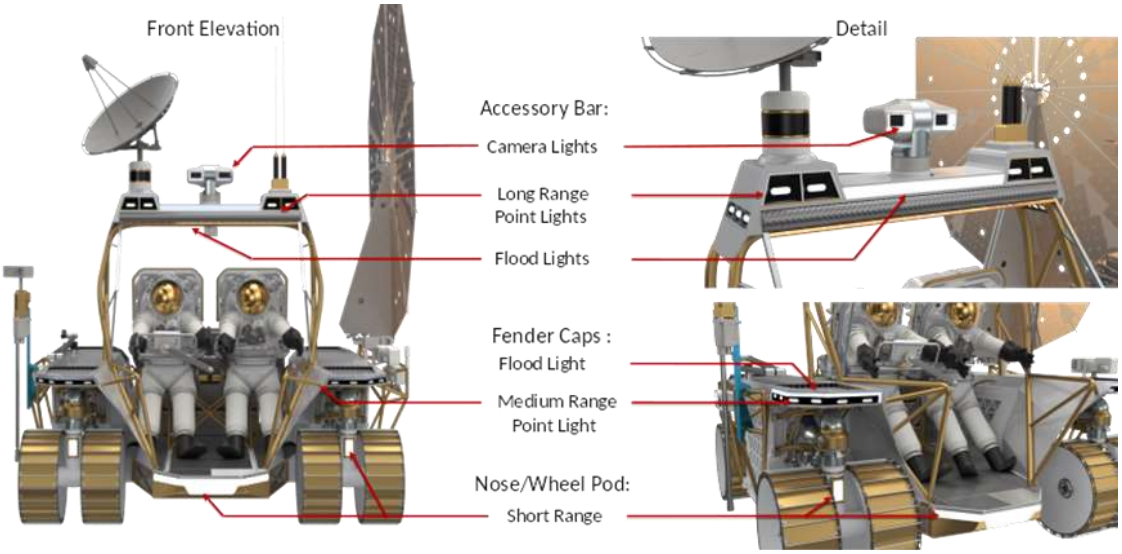


Figure 10. The LTV Option 4 camera and lighting positions.

LTV Light Unit Key

L1-Inside FWD Port Roll Bar
L2-Outside FWD Port Roll Bar
L3-Inside FWD Starboard Roll Bar
L4-Outside FWD Starboard Roll Bar
L5-Inside AFT Port Roll Bar
L6-Outside AFT Port Roll Bar
L7-Inside AFT Starboard Roll Bar
L8-Outside AFT Starboard Roll Bar
L9-Center Work Light
L10-FWD Port Headlight
L11-FWD Center Fog Light
L12-FWD Starboard Headlight
L13-AFT Port Rear Light
L14-AFT Starboard Rear Light

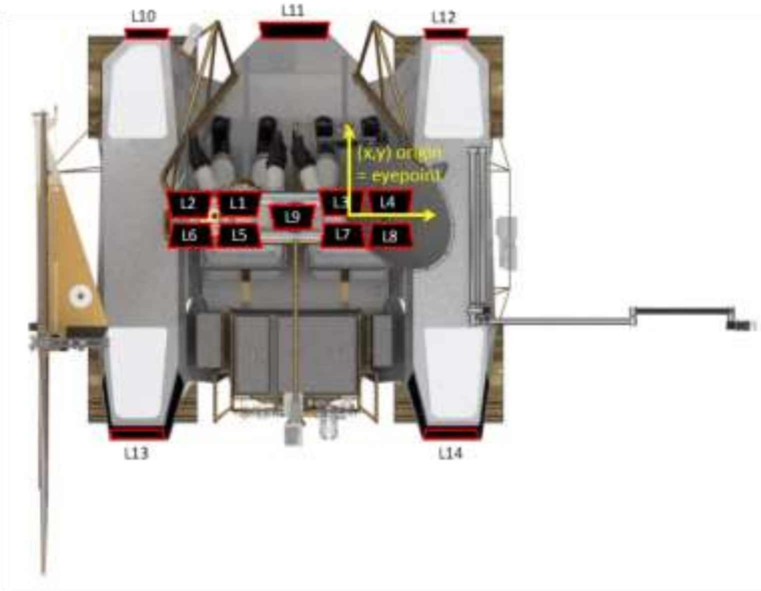


Figure 11. The LTV Option 4 camera lighting unit locations.

Figure 12. The LTV Mast Camera (Axis Q6215-LE).

Table 2. *LTV Mast Camera Specifications*

Resolution	1920 x 1080 @ 60fps
Shutter Speed	1/6 to 1/30,000 secs
Focal Length	6.7 to 201mm f/1.6 to 5.3
Field-of-View	Horizontal: 58.5º to 2.2º Vertical: 34º to 1.2º
Zoom	Optical 30x Digital 21x
Pan/Tilt	Pan Range: 360º @150º/sec Tilt Range: 180º (-90º to 90º) @ 150º/sec
Min Illumination	Color: 0.07 lux B&W: 0 lux
IR Illumination	850nm
IR Range	1300 feet (396.24 meters)

4.3 Simulated Lunar Terrain

The lunar terrain incorporated into the simulation includes a high-fidelity representation of the 16 November 2024 lunar day with the South Pole lunar sun elevation of 1.2º and a notional 500-m radius landing area approximately 17 km from the lunar south pole, as well as a 500-m radius area inside the Bear Paw, approximately 8.9 km west from the landing site (Figure 13). Terrain data was based on 5m/pixel Digital Environment Model (DEM) data and 1m/pixel high-resolution imagery from the Lunar Reconnaissance Orbiter (LRO). This terrain was then augmented with sub-resolution features, such as rocks and craters, based on statistical models. Most of these features were placed using randomization scripts, which aligned with the statistical models generated from LRO imagery (Figure 14 and Figure 15); however, a small subset of craters was carefully placed to align with real crater sizes and positions. This data was provided by scientists in NASA JSC’s Astromaterials Research and Exploration Science Division. A 500-m wide corridor between the landing site and Bear paw area was populated to the same level of fidelity using the same techniques [30].

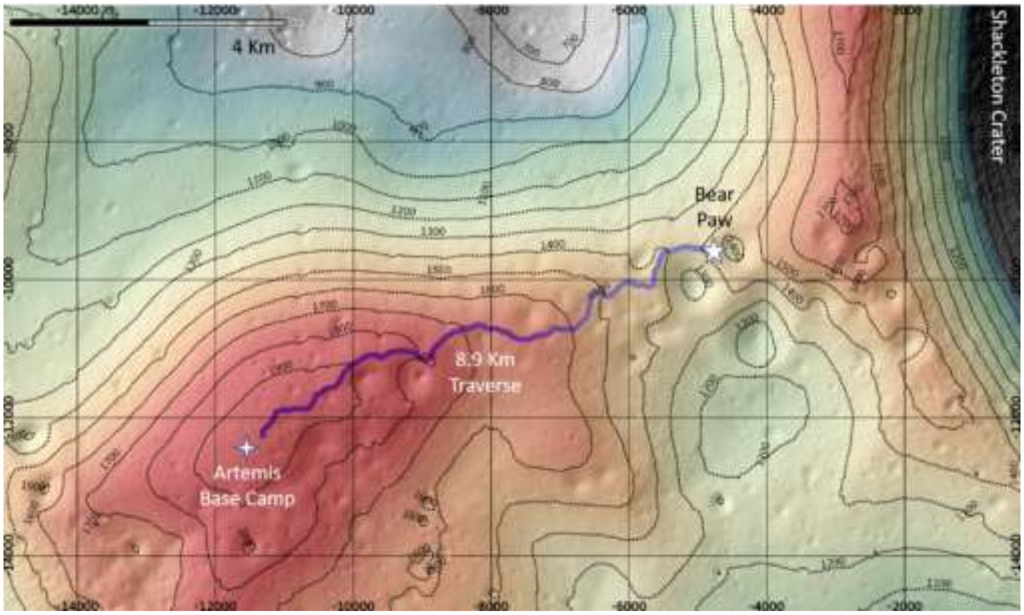


Figure 13. Top-down view of the simulated terrain, noting the Artemis Base Camp and Bear Paw areas with an 8.9 km (5.5 mile) corridor between them.

Figure 14. Screen capture of Artemis Base Camp terrain (notional surface habitat on the right).

Figure 15. Screen capture of Bear Paw terrain.

4.4 Simulated Natural Lighting Environment

The Graphics for Exploration (EDGE) simulation models the environmental lighting using a directional infinite light source providing 127,000 lux of illumination to represent the light from the sun and incorporates Illuminating Engineering Society (IES) profiles for modeling the luminous flux of the artificial lights mounted on the LTV (Figure 16). Contributions to the illumination from reflections off surfaces including Earth shine are currently not being modeled in Engineering DOUG (Dynamic Onboard Ubiquitous Graphics) or EDGE, nor are shadows from light sources other than the sun. The pupillary response in EDGE is currently modeled using an exposure value that computed from a center weighted adapting luminance and key value. [2] The exposure applied before tone mapping is computed by interpolation from previous value to currently computed value using different adaptation times depending on whether the adaption is to an increase or decrease in illumination. To show the resulting High Data Rate (HDR) image onto the Low Data Rate (LDR) display of the SEAL, a global tone mapping operator that approximates the Academy Color Encoding System (ACES) tone mapper with gamma correction is applied. For remote operation paths, an illumination map was constructed for the conditions over the pathway. In Figure 17, the x-axis is time (in days) moving to the right, while the y-axis is distance in km. A flat line in the graph means the rover is stationary at a given location. If the planned traverse is to avoid shadowed terrain, then trip duration can take up to greater than 20 days.

Figure 16. The simulated South Pole Lunar environment.

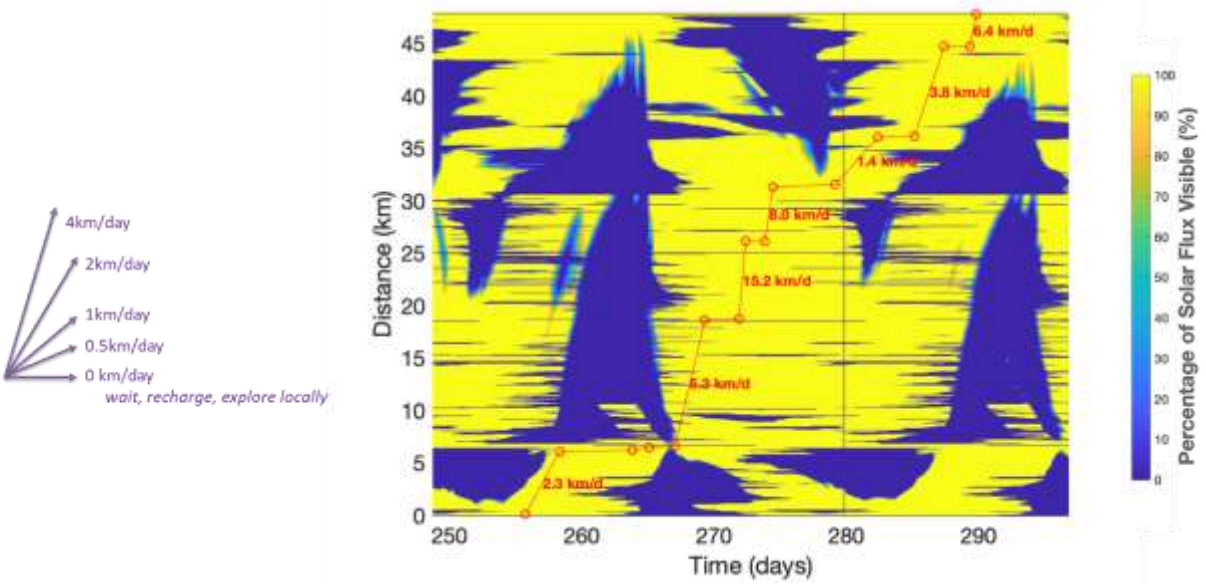


Figure 17. Illumination conditions over pathway graph.

5.0 APRIL 2023 STUDY DESIGN

This testing utilized eight engineering operators with mobility and/or flight operations backgrounds. Test operators were briefed and trained on the six terrain scenarios (Table 3) used in this testing prior to beginning their official evaluation. Each test operator completed each scenario under the two different communication delay conditions (0-s and 4-s roundtrip latency). Each test condition took anywhere from 2 minutes to 15 minutes to complete.

Table 3. *Remote Operation Test Scenarios for April Test*

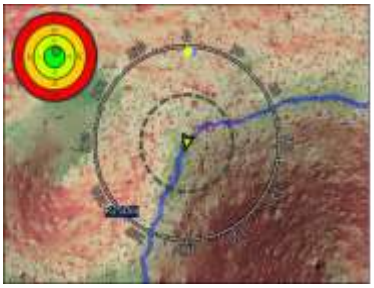
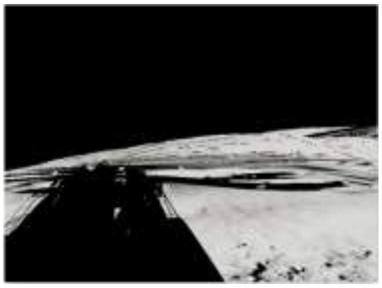
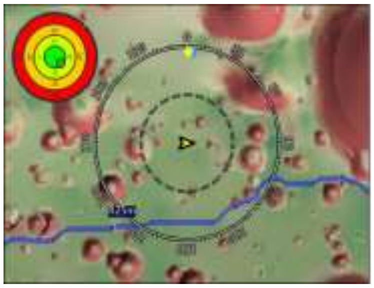
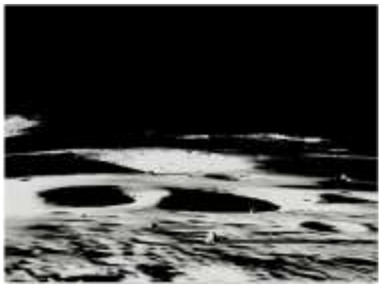
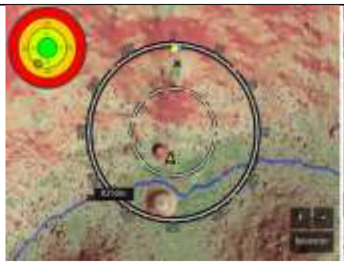
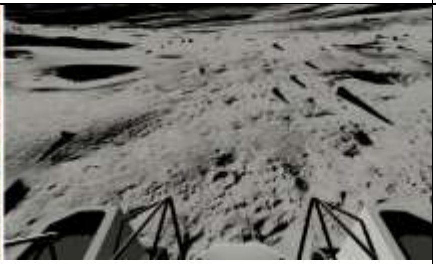
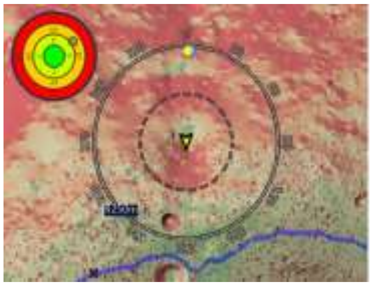
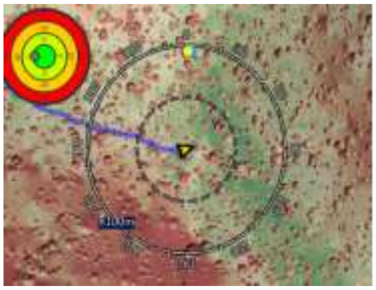
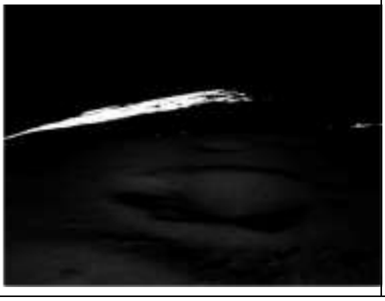
Condition Number	Terrain Scenarios	Nav/Terrain Graphic	Notes
1	Up Sun, Flat	 	Follow desire path for 350m distance
2	Down Sun, Flat	 	Follow desire path for 500m distance
3	Cross Sun, Flat	 	Return to the desired path, then follow desire path for 350m distance
4	Up Sun, Down Slope	 	Return to the desired path, then follow desire path for 300m distance
5	Down Sun, Up Slope	 	Return to the desired path, then follow desire path for 250m distance

Table 3. *Remote Operation Test Scenarios for April Test*

Condition Number	Terrain Scenarios	Nav/Terrain Graphic	Notes
6	Bear Paw Site to Lander Site	 	Follow the desired path to the Lander site for 520m distance

5.1 Test Procedures

Test subjects were given a 15-min familiarization session for each communication delay. Once the familiarization session was complete, the test subject remotely operated the LTV through the six test conditions under the 0-s latency condition (Figure 18). After a quick workload questionnaire and de-brief of the 0-s latency condition, the test subject then remotely operated the LTV through the six scenarios under the 4-s delay (Figure 19). A workload questionnaire and de-brief of the 4-s delay condition was then completed to close out the test.

Figure 18. An operator driving in the 0-s latency condition.

Figure 19. An operator driving in the 4-s latency condition.

5.2 Data Collection

The following objective data was collected during the April 2023 test:

Table 4. *Remote Operation Objective Data Collection*

Data	Units
Total Task Time	seconds
Moving Time	seconds
Stationary Time	seconds
Cruise Control Time	seconds
Average Velocity with Stops	kph
Average Velocity without Stops	kph
Distance Traveled	km
Brake Usage	Frequency of Contact
Rock Contact	Frequency of Contact

As a hypothetical construct, workload represents the cost incurred by a human operator to achieve a particular level of performance [3]. Demands of a certain task is created by the task objectives, duration, structure, and by the human and/or system resources that are provided. For example, mental workload is the difference between cognitive demands of a particular task and the operator's attention resources. [4, 5]. In order to test workload, many researchers state that subjective ratings may come close to actually tapping the essence of workload [3, 4]. The rationale for subjective data in the practical advantages such as, ease of implementation and being non-intrusiveness to collect. One of these standard workload methods is the NASA-Task Load Index (TLX). The TLX has been used in numerous successful multitask contexts such as real [6] and simulated flight tasks [7, 8, 9, 10, 11] and remote-control vehicles [12]. Developed by Hart and Staveland [3], the NASA-TLX uses six dimensions to assess mental workload: mental demand, physical demand, temporal demand, performance, effort and frustration [4]. Definitions of the NASA-TLX dimensions can be seen in Table 5. Six step bipolar scales are used to obtain ratings for each dimension. A score from 0 to 100 is obtained on each scale [4, 3]. The operator is also required to pair comparison between which dimension is more relevant to the workload across all pairs of six dimensions [4]. To combine the six individual ratings into a global score, a weighting procedure is used. The weighting procedure takes the number of times a dimension is chosen as more relevant the weighting for that dimension scale is calculated. An overall workload score from 0 to 100 is obtained for each rated task by multiplying the weight by the individual dimension scale score, summing across the scales, and dividing by 15 (the total number of paired comparisons) [4]. With the NASA-TLX showing a high correlation with performance, an Analysis of Variance (ANOVA) can be carried out on these performance measures in order to check the existence of performance differences associated with workload [4].

Table 5. *NASA-TLX Rating Scale Definitions**

Title	Endpoints	Descriptions
Mental Demand	*Low/High*	How much mental and perceptual activity was required (e.g., thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?
Physical Demand	*Low/High*	How much physical activity was required (e.g., pushing, pulling, turning, controlling, activating, etc.)? Was the task easy or demanding, slow or brisk, slack or strenuous, restful or laborious?
Temporal Demand	*Low/High*	How much time pressure did you feel due to the rate or pace at which the tasks or task elements occurred? Was the pace slow and leisurely or rapid and frantic?
Performance	*Good/Poor*	How successful do you think you were in accomplishing the goals of the task set by the experimenter (or yourself)? How satisfied were you with your performance in accomplishing these goals?
Effort	*Low/High*	How hard did you have to work (mentally and physically) to accomplish your level of performance?
Frustration Level	*Low/High*	How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent did you feel during the task?
*Hart, S.G. & Staveland, L.E. (1988). "Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research," Human Mental Workload, P.A. Hancock & N. Meshkati (Eds.), pp. 239-250. Amsterdam: North Holland Press 1988.		

Observational data was also taken during each test scenario. Additionally, the team asked about the strategy the operator used during the 4-s delay sessions and their overall experience and perceptions of the test.

6.0 AUGUST 2023 STUDY DESIGN

As part of its FY23 strategic analysis cycle, NASA's Exploration Systems Development Mission Directorate (ESDMD) Strategy and Architecture Office (SAO) requested a human-in-the-loop (HITL) test to investigate rover teleoperations conops that support and enhance EVAs. This study was conducted in August 2023. A primary objective was to investigate rover teleoperations under 6- and 8-s round trip communication latencies.

6.1 Test Procedures

Five lunar mission scenarios were conceived and executed for each latency condition, as outlined in Table 6. Test personnel for each scenario included 2 EVA crewmembers and a Mission Control Center (MCC) team that included a capsule communicator (CAPCOM) to talk with the crew, an

EVA officer, and a rover teleoperator. Communication between the crew and CAPCOM was not conducted across a delay due to equipment limitations; however, the remote rover operator was subject to either a 6- or 8-s roundtrip communication delay. Two remote operators served as test subjects for the 10 test sessions (5 scenarios per latency), and each operator received approximately 3 hr of training per latency condition prior to testing.

Table 6. *August 2023 Test Scenarios; Each scenario completed for each latency condition*

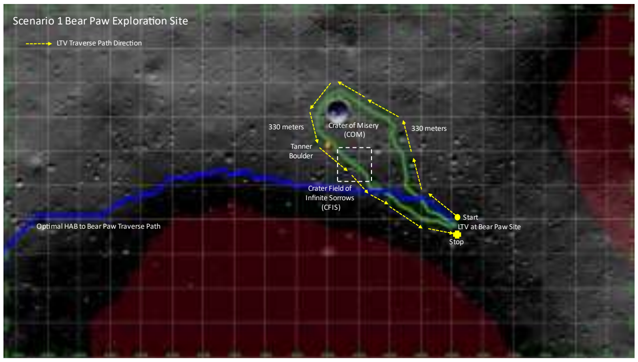
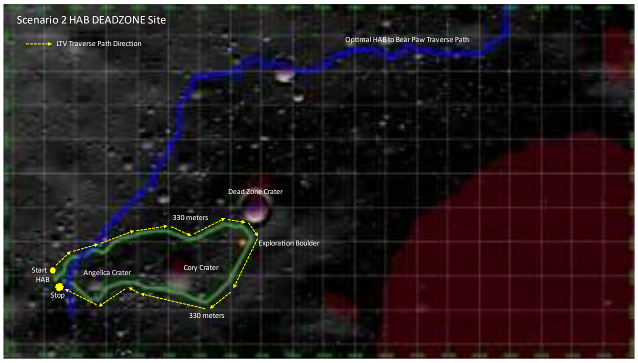
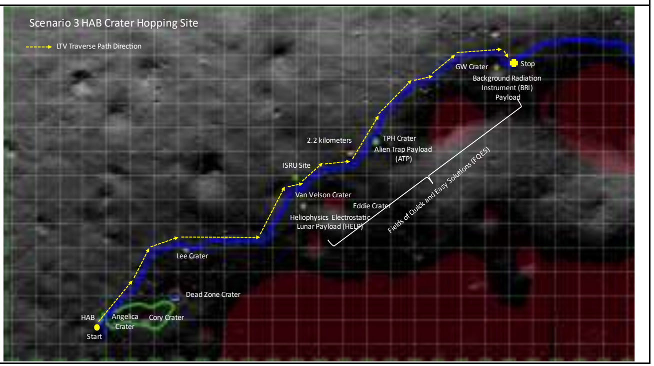
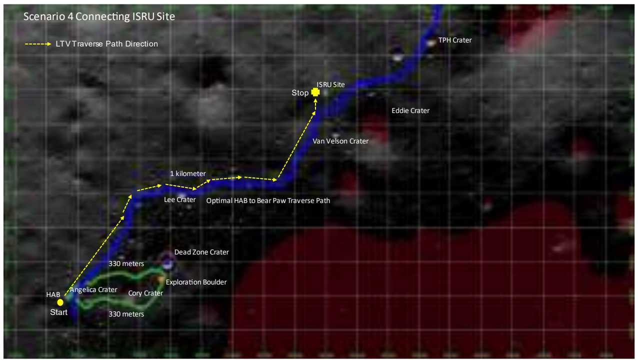
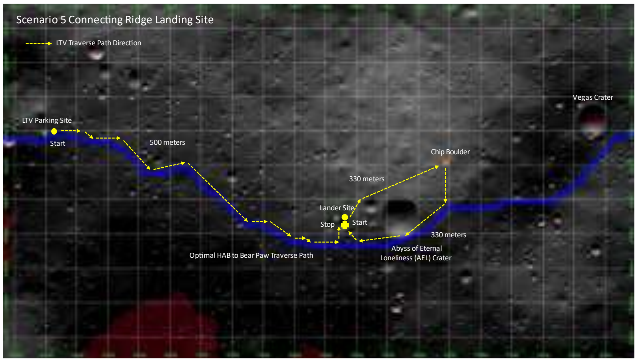
Scenario Number	Scenario	Description	Traverse
1	Bear Paw	At Bear Paw, crew will explore the Crater of Misery (COM) (a 35-meter in diameter large crater) by collecting samples and photographing the area. They will then proceed onto Tanner Boulder to pick up chip samples and photograph. Finally navigate through the Crater Field on Infinite Sorrows (CFIS). The sites are in shadowed lighting areas; however, comm coverage is good. the approximate total distance of the traverse is 660 meters. Will be run twice to test remote ops versus crew driving.	
2	HAB Dead-Zone Site	At the HAB site, the crew will be exploring at Dead Zone Crater where they will be taking samples and photos. The crew will then proceed on foot to a nearby Exploration Boulder collect a chip sample from the boulder and photograph the area. Communications at Dead Zone crater is an issue, and the site is in total shadow when the crew is in the crater. Crew will also collect samples in Cory Crater. Total traverse distance is approximately 660 meters. Will be run twice to test remote ops versus crew driving.	
3	HAB Site Crater Hopping	At the Habitat (HAB) site, crew will be exploring and traverse to multiple crater sites in the Fields of Quick and Easy Solutions (FQES) where they photograph and retrieve 3 small scientific payloads and stow them on the rover. Total traverse distance in approximately 2.2 km. Will be run twice to test remote ops versus crew driving.	

Table 6. *August 2023 Test Scenarios; Each scenario completed for each latency condition*

Scenario Number	Scenario	Description	Traverse
4	In-Situ Resource Utilization unit (ISRU) inspection and parts pickup	Crew will travel approximately 1 kilometer (km) to inspect an ISRU unit on Connecting Ridge from the HAB. Once at ISRU the crew will have the rover do a 360-degree visual inspection of the unit. Then in VR will do a closer inspection and photograph the unit. Next, they will pick up several small parts packages to bring back with them on the rover. Finally, the crew will pick up a few rock samples near unit. Will be run twice to test remote ops and crew driving.	
5	Crew First Day on Moon	At the lander site, the crew has arrived on the Moon and the rover recorded the event for MCC. The rover is 500 meters from the site to protect it from any Foreign Object Debris (FOD) produced by the lander. The crew will descend the Starship Lunar Lander from the elevator approximately 50 meters high and traveling 0.25 meters/second. This will take approximately 3 minutes and 20 seconds. Once on the surface, the crew will first acquire a contingency sample (rocks), do a visual inspection of the lander, then will setup the Artemis flag, and do photography. Once the rover has arrived, crew will inventory the tools on the rover and visually inspected the rover for any damage. Getting aboard the rover, the crew will proceed to Chip Boulder and collect Chip samples. Then on their return trip to the lander, will survey the Abyss of Eternal Loneliness (AEL) Crater. Will be run twice for with different remote ops delays. Total traverse is 1.2 km.	

6.2 Data Collection

Both objective and subjective data were collected as part of the August 2023 study (Table 7).

Table 7. *Objective and Subjective Collection of Data*

Data Units	Data	Data Description	Element	Data Type
km	Distance	The total km the crew drove the rover for a specific task	Remote Ops	Objective
kph	Average Speed	The average speed the crew drove the rover for a specific task	Remote Ops	Objective
kph	Average Velocity with Stops	The average speed with stops the crew drove the rover for a specific task	Remote Ops	Objective
kph	Average Velocity without Stops	The average speed without stops the crew drove the rover for a specific task	Remote Ops	Objective

Table 7. *Objective and Subjective Collection of Data*

Data Units	Data	Data Description	Element	Data Type
seconds	Moving Time	The average moving time the crew drove the rover for a specific task	Remote Ops	Objective
seconds	Stationary Time	The average stationary time the crew stopped the rover for a specific task	Remote Ops	Objective
seconds	Cruise Control Time	The cruise control time the crew used while driving the rover for a specific task	Remote Ops	Objective
seconds	Total Drive Time	The total drive time the crew drove the rover for a specific task	Remote Ops	Objective
seconds	Time Delay	Two-time delay conditions of 6 and 8 seconds for remote operations	Remote Ops	Objective
#	Brake Usage	Number of brake inputs	Remote Ops	Objective
N/A	NASA TLX Workload	Workload ratings for each specific scenario	Remote Ops	Subjective
N/A	Driving Strategies	Driving strategies under different comm delays	Remote Ops	Subjective

7.0 RESULTS AND DISCUSSION

For the April study, a total of eight operators participated in the testing. A majority of the participants had a gaming background and some 4x4 off-road driving experience. Backgrounds of subjects range from flight operations to remote robotic operations and Systems Engineering, and Integration (SE&I) leads from both the LTV program and the PR program. Capabilities the subjects have available to them during testing was a single remote operations high-definition camera view, a joystick controller, two 38-centimeter (cm) monitors with navigation support and rover telemetry, assuming a perfect high bandwidth communications coverage using the notional government reference LTV with its’ associated performance and terramechanics models. Each subject was in testing for a minimum of three hours in NASA’s SEAL facility and tested the two communication conditions over six different scenarios.

After all driving scenarios were completed, test operators provided responses to the following questions to provide insight into the primary objective metric of interest (e.g., average teleoperations driving speed) for this study:

1. General feedback with respect to what it’s like to drive in this environment: terrain + natural lighting (i.e., how much do you think the terrain and natural lighting impact your driving speed?).
2. General feedback with respect to driving under a 4 second latency (i.e., how much do you think this latency impacted your driving speed?).
3. Did you have enough training, especially with regard to the 4 second latency? Assuming no, how much training do you think you would need>?
4. What strategy did you use to remotely operate the rover under the 4 second latency?
5. General feedback with respect to the remote operations workstation and console (e.g., sim quality or ergonomic issues with the hand controller, display, etc.) that might have impacted your driving speed? (Note that this was not a hand controller, display, etc, study – a vendor may provide something completely different).

The August Study used lessons learned from the Desert Research and Technology Studies (DRATS) FY22 field analog with the PR, the investigative team noted how surprisingly complicated rover tele-ops conops could be and the significant forward work that remained in order to best understand the conops for rover use to support and enhance Extravehicular Activities (EVA). A key discovery from DRATS-22 was that there may often be an operation tradeoff between some desirable features a rover brings to surface exploration with crewed EVAs, such as a desired for proximity to the EVA crew for enhanced lighting or tool and sample carrying. There was also a desire to understand the distance the rover needed to be from the EVA crew. Therefore, a recommendation from DRATS-22 was to use the Lighting and Navigation Simulation to further investigate the operational implications. For the August 2023 study, five different traverse scenarios were developed and tested with astronaut subjects. Subjects drove the LTV and communicated with MCC on a non-delayed basis; however, the MCC remote operator operated the vehicle in a 6- and 8-s communications delay with the signal path as a Direct To Earth (DTE) connection. Since the five scenarios were all different types of traverses, data analysis was first conducted on each scenario to obtain a clear picture of why the remote operator handled the vehicle in the two new communication delays. Then an overall average across scenarios was calculated for each latency. As a note, the speed without stops was not calculated in this Phase 2 study as the stops were pre-planned and recorded as stationary time for the vehicle.

The following sections will reveal the results for the 0-s, 4-s, 6-s and 8-s latency conditions. Rationale for collecting 0-s latency data was for the investigators to analyze using an established data set without a delay variable when comparing the data from the 4-s delay condition. However, between the April study and the August study, the Artemis communications team updated their communication latency calculations. Earlier a 4-second latency directly from the vehicle to Earth has been estimated as the longest delay; however, further analysis from the communications team found the earlier estimated to be untrue as the communication delay increased. The estimated times for communication delays are now 6 to 8-seconds in roundtrip duration. This is due to the Deep Space Network (DSN) not being designed to have a high-speed communication bit rate planned into the system. The system was originally design for slower communication speeds to accommodate distant rovers (e.g., Mars) and satellites which do not have high speed communications systems installed on the space craft.

Objective data that was collected consists of Speed With Stops (all stops the subject did is included in this metric, in kilometer per hour (kph) (all latencies); Speed Without Stops (the stops were taken out of the analysis in kph)) (only 0-s and 4-s latencies), Distance Traveled (in meters), Time Moving (time the vehicle was moving in seconds (s)), Time Stationary (time the vehicle was standing still in seconds), Total Task Time in seconds, Cruise Control Time (time the subject spent in cruise control in seconds), Brake Inputs (count of how many times the brake was used by the subject), Rock Contact 0.15 to 0.37 meters (m) above the surface (count of rock contracts), Rock Contact 0.38+ m, and Total Rock Contracts (only 0-s and 4-s latencies). The objective data was collected through log simulation files. Statistical analysis for the objective data used descriptive statistics. Rationale for using the Paired *t*-Test was used to determine whether the mean difference between two sets of observations is zero in a case-controlled studies or repeated-measures designs.

Subjective data included subject workload using the NASA-TLX, driving strategies, and general comments on the simulation environment, the 4-s, 6-s, and 8-s delay environments and training time for proficiency. Workload was analyzed by the six individual elements and by total workload using the analysis of variance (ANOVA).

7.1 Speed

Two average speeds were computed for each test operator's trial, as well as across all trials and all subjects for a given latency condition:

- Average Speed Including Stops (i.e., "speed made good"): average speed, including time spent stationary (vehicle fully stopped) (all latencies)
- Average Speed Without Stops: average speed excluding time spent stationary. This results in a "purer" vehicle speed (0-s and 4-s latencies only)

All speeds were collected in meters per second (m/s), then converted into kilometer per hour (kph) for easier understanding.

7.1.1 Speed Results for 0-s and 4-s Latencies

The 0-s latency condition was implemented to familiarization the operators with both the South Pole simulated terrain and the actions of the vehicle. Investigators used this data as a reality-check on how the operator operated the vehicle as if on the lunar surface with no communications anomalies. This gave the investigators a sounding block when comparing the 4-s delay data. For the 0-s delay, an average speed was calculated for each operator in each scenario. A descriptive analysis was conducted across all operators and scenarios to obtain an overall average speed. A paired-samples *t*-test was conducted to compare the speed during a 0-s delay with stops added and without stops. There was a significant increase in speed when stops were not included (*M* = 3.80, SD = 2.05) than when stops were included (*M* = 3.24, SD = 1.97); *t*(47) = -6.68, *p* = < .001 (Table 8).

Table 8. *Speed Data Across All Operators and Scenarios for 0-Second Latency*

	Speed w/Stops (kph)	Speed w/o Stops (kph)
Mean	**3.24**	**3.80**
Standard Error	0.28	0.30
Standard Deviation	1.97	2.05
Minimum	0.00	0.00
Median	2.84	3.79
Maximum	7.60	8.16

In the 4-s delay condition, speeds in both cases decreased due to the operator having to form a strategy on how to handle communications delay while inputting commands to the vehicle. The overall average across subjects and scenarios used descriptive statistics. As with the 0-s delay condition, a paired-sample *t*-test was conducted to compare the speed in a 4-s communications delay with and without stops. As seen with the 0-s delay case, in the 4-s delay condition there was a significant increase in speed when stops were not included (*M* = 3.55, SD = 1.55) than when stops were included (*M* = 2.56, SD = 1.43); *t*(47) = -10.07, *p* = <. 001 (Table 9).

Table 9. *Speed Data Across All Operators and Scenarios for 4-Second Latency*

	Speed w/Stops (kph)	Speed w/o Stops (kph)
Mean	**2.56**	**3.55**
Standard Error	0.21	0.22
Standard Deviation	1.43	1.55
Minimum	0.94	1.26

Table 9. *Speed Data Across All Operators and Scenarios for 4-Second Latency*

	Speed w/Stops (kph)	**Speed w/o Stops (kph)**
Median	2.06	3.18
Maximum	6.62	7.54

When comparing the two delayed communication conditions with stops included with the average speed, the average 0-s delay speed was calculated at 3.24 kph while the 4-s delay was 2.56 kph. A paired-samples *t*-test was conducted to compare the speed with stops across the two communications delayed conditions. There was a significant increase in speed in the 0-s latency configuration with stops (*M* = 3.24, SD = 1.97) than in the same condition under a 4-s latency configuration (*M* = 2.56, SD = 1.43); *t*(47) = 2.26, *p* = .028. Calculating the delta between the two speeds (0.68 kph), speeds in the 0-s latency condition was 12% faster when compared to the 4-s latency configuration. However, when examining the speed without stops included, analyze indicates a different outcome. With stops taken out, a pure vehicle speed is realized; thus, in the 0-s latency condition the average speed was 3.80 kph with the 4-seond latency speed being 3.55 kph. In this case, the paired-samples *t*-test showed non-significant difference between the 0-s delay speed (*M* = 3.80, SD = 2.05) and the 4-s delay speed (*M* = 3.55, SD = 1.55); *t*(47) = 0.72, *p* =.475. Calculating the delta between the two speeds (0.25 kph), speeds in the 0-s latency condition was only 4% faster when compared to the 4-seond latency configuration. Therefore, in both delay situations the speed was significantly quicker when stops were excluded. Additionally, when contrasting speeds that included stops across the communication delays, operators were significantly faster in the 0-s latency condition when compared to the 4-s latency condition. However, when comparing speeds where the stop was excluded, there was no significant difference between the communication delay conditions.

In situations such as remote driving the rover on the lunar surface, a time-delay in the order of seconds can readily result in a dangerous state where the roving vehicle is either damage or loss compromising the entire mission. Considered minimal teleoperation experience and training, plus having only one camera view with rover telemetry transmitted through a high bandwidth flawless communications signal with faultless navigation, results indicated a very conservative average of two speed variations which achieved the stated requirement over a test estimated 1.5 kilometers distance (Table 10). The average speed was calculated across all test conditions and operators for both the speeds with stops and speed without stops (speed made good) situation. The distances are by the LTV SRD requirements. Time was derived from dividing distance by speed.

Table 10. *Average Speeds for Remote Operations of the Lunar Terrain Vehicle For Two Communication Delays*

Communication Delay	Speed with Stops			Speed without Stops		
	Average Speed (kph)	Distance (km)	Time (hh:mm:ss)	Speed (kph)	Distance (km)	Time (hh:mm:ss)
0-Second Latency	3.24	6 [a]	1:51:07	3.80	6	1:34:44
		8 [a]	2:28:09		8	2:06:19
		20 [b]	6:10:22		20	5:15:47
4-Second Latency	2.56	6	2:20:38	3.55	6	1:41:25
		8	3:07:30		8	2:15:13
		20	7:48:45		20	5:38:02

Note[a]: LTV-SYS-071 6km (threshold), 8km (goal) distance in one 24-hour period when operated remotely
Note[b]: LTV-SYS-029 no less than 20km without stopping for recharge

7.1.2 Speed Results for 6-s and 8-s Latencies

An average speed was computed for each test scenario, as well as across all scenarios and all subjects for a given latency condition:

- Average Speed Including Stops (i.e., "speed made good"): average speed, including time spent stationary (vehicle fully stopped)

For the 6 and 8-s delays, an average speed was calculated for each operator in each scenario for each latency. A descriptive analysis was conducted across all operators and scenarios to obtain an overall average speed (Table 11). When comparing the two delayed communication conditions with stops included with the average speed, the average 6-s delay speed was calculated at 2.03 kph while the 8-s delay was 1.76 kph. A paired-samples *t*-test was conducted to compare the speed with stops across the two communications delayed conditions. The *t*-test showed a non-significant difference between the 6-s delay speed (*M* = 2.03, SD = 0.76) and the 8-s delay speed (*M* = 1.76, SD = 0.67); *t*(4) = 0.46, *p* =.336. The delta between the two latency speeds was a mire 0.27 kph.

Table 11. *Speed Data Across All Operators and Scenarios*

	Speed w/Stops (kph)	
	6-second	8-second
Mean	**2.03**	**1.76**
Standard Error	0.43	0.39
Standard Deviation	0.76	0.67
Minimum	1.29	1.10
Median	1.99	1.73
Maximum	2.8	2.45

Remote driving on the lunar surface can be challenging with no communication latency; however, with a time-delay, on the order of 6 to 8-seconds, can result in a dangerous state where the vehicle is either damage by contacting a large rock or loss due to falling into a deep crater compromising the future missions. The operators for this study had minimal teleoperation experience and training on the order of 3 hours, plus having only one camera view with rover telemetry transmitted through a high bandwidth flawless communications signal with faultless navigation. Results indicated a very conservative average of speed variations which achieved the stated distance requirement in LTV-SYS-071 and the minimal 20 km distance on a single battery charge for the LTV-SYS-029 requirement. Table 12 illustrates the average speeds, requirement distance, and time.

Table 12. *Average Speeds for Remote Operations of the LTV for Two Additional Communication Delays*

Communication Delay	Speed with Stops		
	Speed (kph)	Distance (km)	Time (hh:mm:ss)
6-Second Latency	2.03	6 [a]	2:57:20
		8 [a]	3:56:27
		20 [b]	9:51:08
8-Second Latency	1.76	6	3:24:33
		8	4:32:44
		20	11:21:49

Note[a]: LTV-SYS-071 6km (threshold), 8km (goal) distance in one 24-hour period when operated remotely

Note[b]: LTV-SYS-029 no less than 20km without stopping for recharge

7.2 Distance

For the two studies, the distance is either the total amount of a complete scenario or the individual scenario itself. All distances were collected in meters and then, when feasible, was converted to kilometers.

7.2.1 Distance Results for 0-s and 4-s Latencies

Distance traveled is the cumulative distance all test operator for each latency condition. Operators experienced several different lighting conditions, slopes, and highly cratered areas. In the 0-second latency condition, the operators traveled a total of 15.9 km when compared to 15.2 km in the 4-second latency condition. There is only a 2% (700 meters) difference between the distances travel in the two communication conditions. The differences between the distances comes from a testing time constraint of three hours. Some operators took longer in the 0-s latency condition forcing the test team to reduce some of the distances in the 4-s latency condition.

7.2.2 Distance Results for 6-s and 8-s Latencies

The total distance traveled in both latencies was 5.1 kilometers (km). Overall averages of distances per latencies across all scenarios indicates a 20% increase in distance from 6-s (596.6 meters) to 8-s (872.37 meters) (Table 13). The main factor causing this differential in distance between was the traverse distance in Scenario 4A and B. In this scenario, the remote operator partially drove the rover back from the ISRU unit to the HAB site approximately 1.04 km (Figure 20. The traverse course from the HAB site to the ISRU site. This was the longest traverse made by the remote operator across all the scenarios. A paired-samples *t*-test was conducted to compare the amount of distance travel across the two communications delayed conditions. The *t*-test showed a non-significant difference between the 6-s delay distance (*M* = 596.6, SD = 458.35) and the 8-s delay distance (*M* = 872.37, SD = 158.13); *t*(2) = -0.985, *p* =0.214.

Table 13. *Distance Data Across All Operators and Scenarios*

	Distance (m)	
	6-second	**8-second**
Mean	**596.60**	**872.37**
Standard Error	264.63	91.29
Standard Deviation	458.35	158.13
Minimum	67.80	721.40
Median	842.00	858.90
Maximum	880.00	1036.80

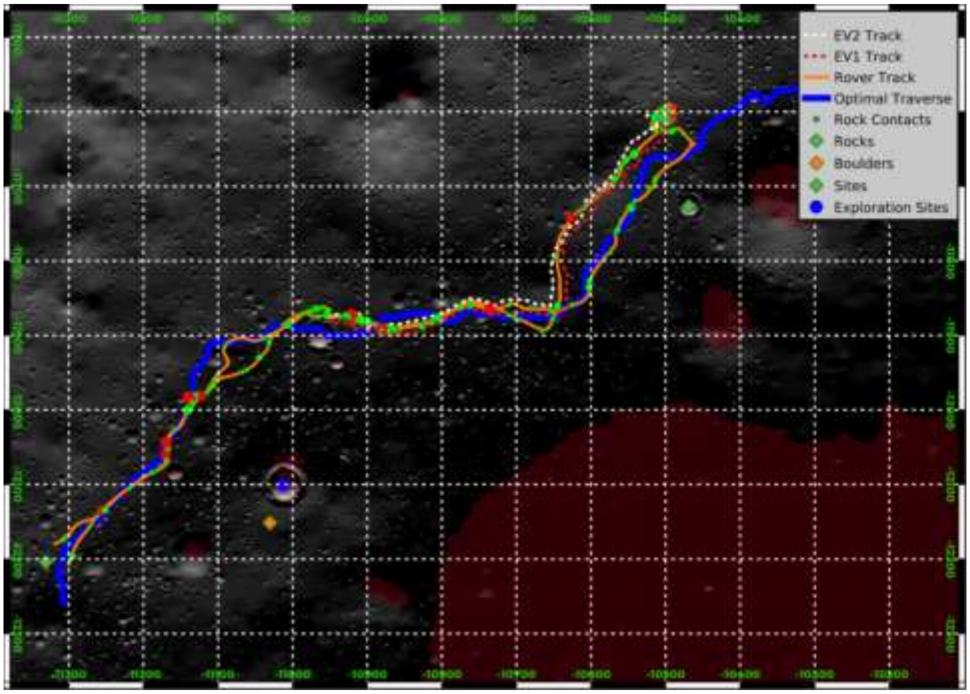


Figure 20. The traverse course from the HAB site to the ISRU site.

7.3 Time

Time was distributed and calculated in four domains: 1) Moving Time, 2) Stationary Time, 3) Cruise Time and 4) Total Task Time. All time is reported in hours minutes seconds. The moving time is the time the vehicle is actually moving from one point to another. Stationary timing is the time the vehicle has stopped and sitting. Time for using the cruise control is considered the cruising time. Lastly, the total task time is the time for the total remote operation tasks from beginning to end. All time was recording in seconds and investigators did convert the seconds in hours, minutes, seconds for an easier understanding.

7.3.1 Time Results for 0-s and 4-s Latencies

The cumulative time spent driving, which include time moving plus stationary time by all test operators for the 0-s latency was 5 hours 3 minutes and 54 seconds. In the 4-s latency, the cumulative time spent driving was 7 hours 31 minutes and 38 seconds. Cruise control time is the time the subject had the vehicle in cruise control. Of all the time domains this time was the shortest among operators. Cumulative time spent driving while using cruise control by all test operators for the 0-s latency was 57 minutes, while in the 4-s latency condition, operators spent 1 hour 24 minutes and 3 seconds (Figure 21). Due to the slower speeds that were noted in the 4-s delay condition, times were affected in the domains of total task time, moving time, and stationary time. Each of these domains showed a significant increase when compared to the same times in the 0-s latency condition. Also contributing to the time difference, it was observed that operators were being more cautious at avoiding hazards and they tended to increase their route planning before making a vehicle command. However, for the cruise control time where no difference was seen between the communication delays, the number of operators who opted to used cruise control was small. Of the eight operators, only three opted to use the cruise control. Of that three, two of them used the cruise control during the 0-s latency configuration while all three used the cruise control in the 4-s latency configuration. The five operators who opted out of using the cruise control, opted out in all the communication delay condition.

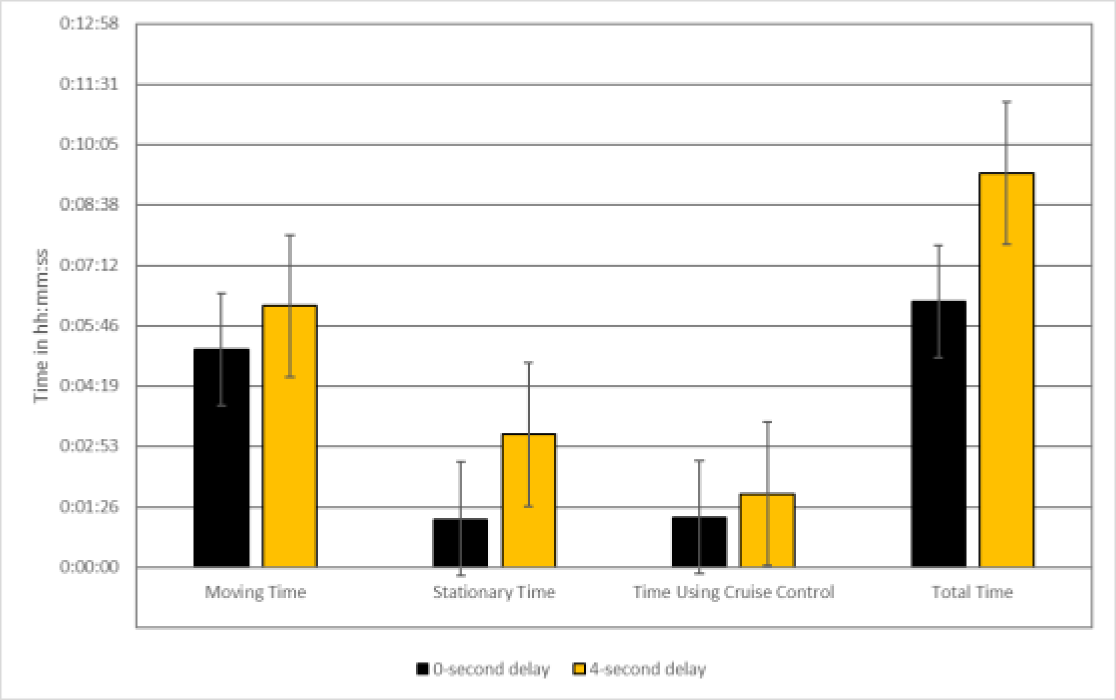


Figure 21. Average time across all operators spent on driving in a 0-s and 4-s delay.

7.3.2 Time Results for 6-s and 8-s Latencies

Using the same timing protocol as in the April 2023 study, investigators examined the time the vehicle was moving, the stationary time when the vehicle was stopped and sitting still, and the amount of time the remote operators used the cruise control speed function. For the overall average across scenarios while in a 6-s delay, the operator drove the vehicle 17 minutes and 27 seconds. In the 8-s latency, the operator increased their time moving by 24% for a total of 28 minutes and 40 seconds (Figure 22). A paired-samples *t*-test was conducted to compare the amount of moving time across the two communications delayed conditions. The *t*-test showed a non-significant difference between the 6-s delay moving time (M = 1047, SD = 821.1) and the 8-s delay moving time (M = 1720.3, SD = 933.5); $t(4) = -0.938$, p =0.2. The increase in time is mainly due to the longer duration latency, terrain, and operator confidence. Stationary time is the time the vehicle spent stopped. For the 6-second latency, the remote operators had the vehicle stopped for 43 minutes and 15 seconds, while in the 8-second latency the time was only 15 minutes and 56 seconds. This is an increase of 44% in the 6-s condition compared to the 8-s condition. A paired-samples *t*-test was conducted to compare the amount of stationary time across the two communications delayed conditions which indicated no-significant difference between the 6-s delay stationary time (M = 2596.7, SD = 2872.8) and the 8-s delay stationary time (M = 1016.7, SD = 441.6); $t(2) = -0.94$, p =0.22. The major factor effecting the stationary time was Scenario 1A and B as the rover had to navigate through an extensive crater field (the Crater Field on Infinite Sorrows) in order to get back to the base point of the traverse (Figure 23). Cruise was used by the remote operators in both latencies. In the 6-s latency, the operators used cruise control for 17 minutes and 11 seconds, compared to the 8-s latency where the operators used cruise for 27 minutes and 56 seconds. This is a 24% increase in cruise time. The largest cruise times were recorded in the 8-s latency scenarios of 2A and B and 4A and B. A paired-samples *t*-test was conducted to compare the amount of cruise time across the two communications delayed conditions. The *t*-test showed a non-significant difference between the 6-s delay cruise time (*M* = 1013, SD = 823.8) and the 8-s delay cruise time (*M* = 1076.7, SD = 912.1); *t*(4) = -0.935, *p* =0.2. It was observed and reported the remote operators had started to become accustomed to the delay and to offset their workload setting the cruise control for a comfortable and maneuverable speed was beneficial. This concurs with the 4-s results on workload.

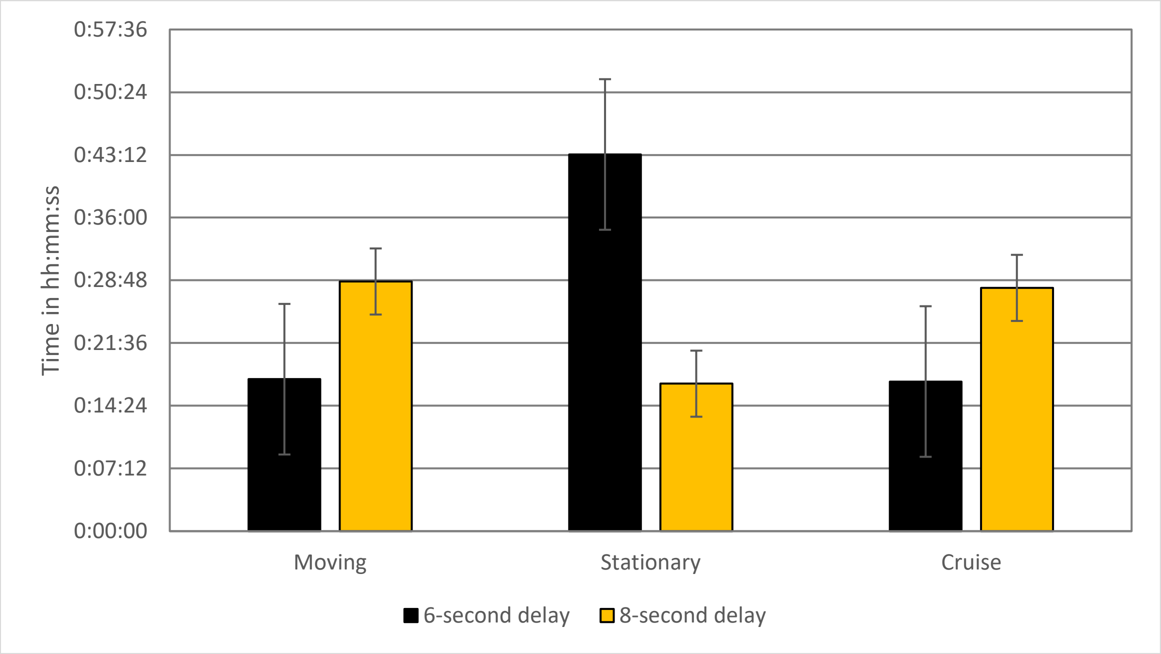


Figure 22. Average time across all operators spent on driving in a 6-s and 8-s delay.

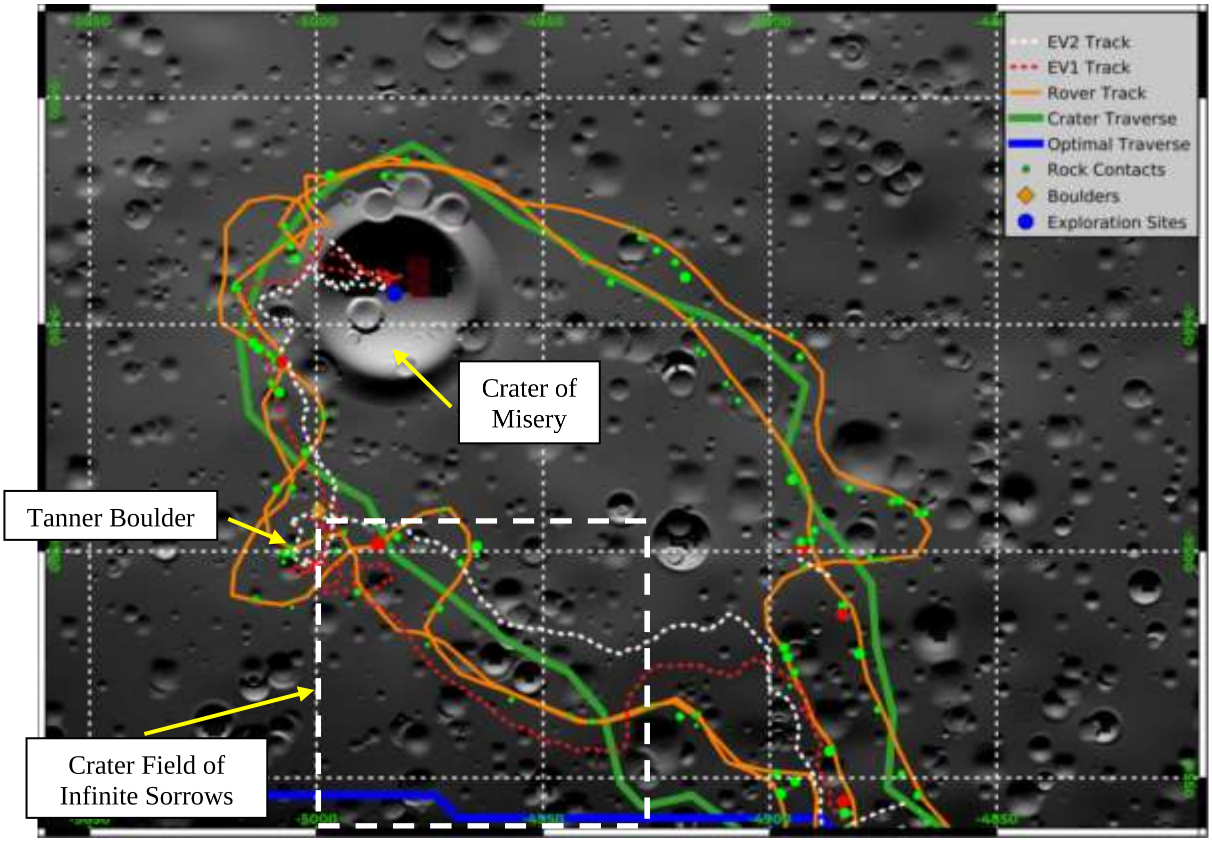


Figure 23. The rough terrain in the Crater Field of Infinite Sorrows.

7.4 Brake Usage

In order to stop the vehicle, the act of braking was accomplished by pulling a trigger switch under the head of the hand controller or pushing a white button on the hand controller head to engage the vehicle’s park brake. There was an added brake for the August study call the emergency brake or e-brake. For the April study, the only braking data was pedal brake. However, in the August study all three types of brake usage data collected during the study: 1) Emergency brake (e-brake), 2) Pedal brake (momentary braking e.g., like a car brake pedal), and 3) Park brake.

7.4.1 Brake Usage Results for 0-s and 4-s Latencies

Subjects braked the vehicle a total of 4,326 times across while driving the six scenarios across two communication delays. The 4-s latency condition observed the most braking with 3,873 (90%), while the 0-s latency condition had only 453 times (10%) the brake was used. Thus, operators braked 80% more in the 4-s delay than in the 0-s delay. This is mainly due to terrain features with lighting conditions and in both communication cases. Of the six scenarios that were driven by the operators, scenario six which is where the operators started off at a scientific site at Bear Paw in a shadowed area that had a high number of craters, caused the operators to do the most braking. Operators indicated that braking was used more frequently in the 4-s latency condition due to a start-stop strategy where five of the eight operators used to avoid rocks and craters while managing slipping on slopes of 5 degrees or greater. The 4-s delay made decision making more challenging causing operators to be more vigilant when compared to the 0-s delay situation. The slope strategy had the operator using the brake to keep the vehicle still before inputting a driving command.

7.4.2 Brake Usage Results for 6-s and 8-s Latencies

The overall usage of braking was 42% higher in the 8-s latency condition (106 times) when compared to the 6-s latency condition (43 times). A paired-samples *t*-test was conducted to compare the amount of overall brake usage across the two communications delayed conditions. The *t*-test showed a slightly significant difference between the 6-s delay brake usage (*M* = 4.78, SD = 9.05) and the 8-s delay brake usage (*M* = 11.78, SD = 9.48); *t*(16) = -1.6, *p* =0.06. The majority of the e-braking occurred in Scenarios 2A and B and 4A and B. These two scenarios had the crew following the rover more than in the 6-s latency scenarios. Scenario 2A and B had a major crater field between Cory Crater and Angelica Crater where the crew tended to use the e-brake more while navigating the remote rover through the crater field (Figure 24). Scenario 4A and B was where the remote operator circled around the ISRU to inspect the hardware while crew observed the maneuver. They would use the e-brake to keep the vehicle from contacting the sensitive hardware (Figure 25). Table 14 shows the further distribution of each braking type used in the two latency configurations. Taken individually, none of the braking types show any significant between latencies; e-brake 6-s delay (*M* = 0.67, SD = 0.58) and the 8-s delay brake usage (*M* = 4.33, SD = 3.78); *t*(2) = -1.66, *p* =0.12; pedal brake 6-s delay (*M* = 0.00, SD = 0.00) and the 8-s delay brake usage (*M* = 11.3, SD = 11.5); *t*(2) = -1.71, *p* =0.12; and park brake 6-s delay (*M* = 13.67, SD = 12.22) and the 8-s delay brake usage (*M* = 19.67, SD = 6.02); *t*(3) = -0.76, *p* =0.25.

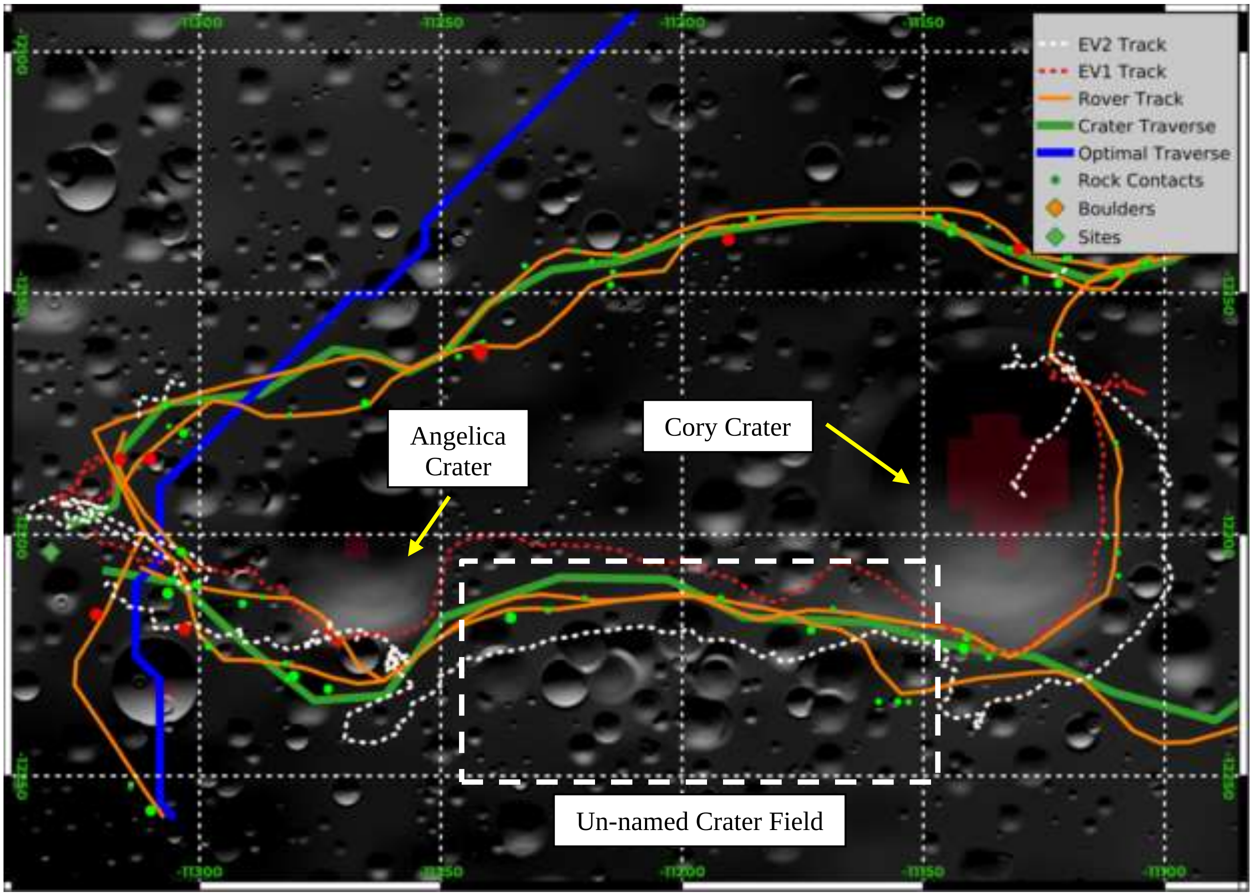


Figure 24. The traverse course for Scenario 2A and B. Note the crater field where most of the e-braking took place.

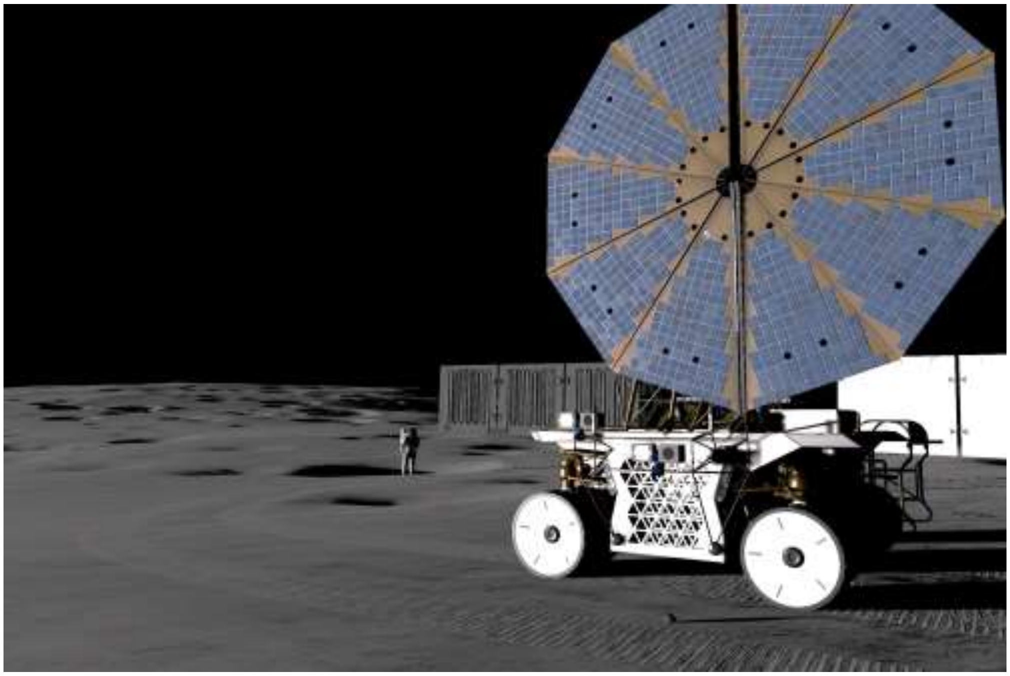


Figure 25. Crew aiding remote rover around ISRU.

Table 14. *Brake Usage Data Across All Operators and Scenarios*

	Brake Usage					
	6-second			8-second		
	e-brake	pedal brake	park brake	e-brake	pedal brake	park brake
Mean	**0.67**	**0.00**	**13.67**	**4.33**	**11.33**	**19.67**
Standard Error	0.33	0.00	7.05	2.18	6.64	3.48
Standard Deviation	0.58	0.00	12.22	3.78	11.50	6.03
Minimum	0.00	0.00	3.00	0.00	0.00	14.00
Median	1.00	0.00	11.00	6.00	11.00	19.00
Maximum	1.00	0.00	27.00	7.00	23.00	26.00

7.5 Rock Contact

Rock contacts while driving can lead to vehicle damage, either immediately upon impact or over time, depending on the size of the rock and speed the vehicle is traveling during impact. The simulation rock contact model shows the impact location of the rock on the vehicle. There are two sizes of rock heights that are automatically recorded. Rocks between 0.15 to 0.37-meter (m) to heights above the surface that were hit by the vehicle during the driving trails and flagged "green" based on a notional LTV dynamics model. Hitting rocks of this height were unlikely to render severe vehicle damage instantaneously; however, if the vehicle repeating hits this size of rocks it could lead to sustained damage over time. Rocks greater than 0.38m above the lunar surface were also hit by the vehicle and flagged "red." Rocks of this height could cause severe instantaneous vehicle damage.

7.5.1 Rock Contact Results for 0-s and 4-s Latencies

During the April study, the cumulative number of rock contacts for all operators over all terrain scenarios was calculated. For the 0-s latency condition, 812 green contacts were recorded plus 49 red contacts making for a total number of 861 rock contacts on the vehicle. In the 4-s latency condition, 906 green contacts were recorded plus 53 red contacts making a total number of 959 rock contacts. A paired wise *t*-test confirms there was not a significant difference between the number of rock contacts for rocks that are 0.15 to 0.37 m in height in the 4-s delay (*M* = 121.57, SD = 52.96) and the 0-s delay (*M* = 97.28, SD = 64.62); *t*(6) = -0.922, *p* = .391 as well as 0.38m+ rock contracts in a 4-s delay (*M* = 7.43, SD = 3.90) when compared to a 0-s delay (*M* = 5.85, SD = 6.01); *t*(6) = -0.80, *p* = .453. Modeling the rock contact as to where the rock hit the vehicle indicated the majority occurred at the front of the rover and were consistent across subjects (Figure 26).

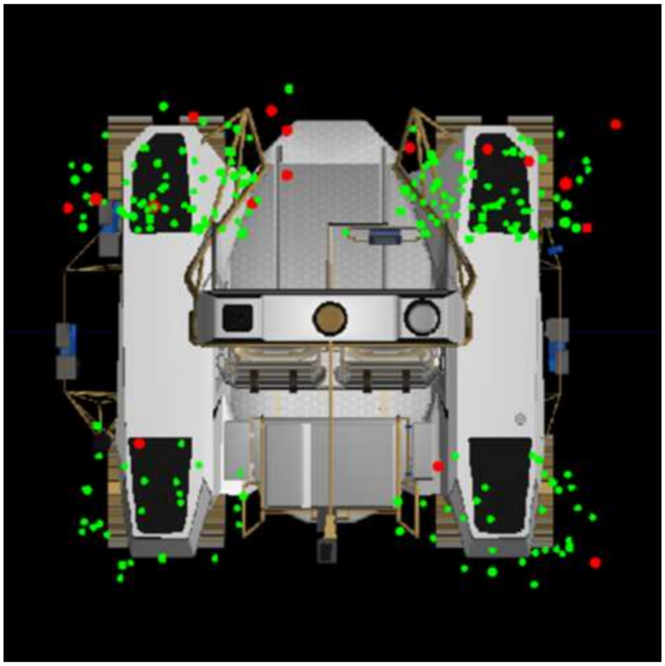


Figure 26. Rock contacts from one representative test subject for all trials in the 0-s latency conditions. Green dots equal rock heights between 0.15 to 0.37m, whiel red dots equal rock heights > 0.38m.

7.5.2 Rock Contact Results for 6-s and 8-s Latencies

Though rock contacts were recorded during the August study for 6-s and 8-s latencies, due to haivng five different scnearios the data was deemed not approate for this particular test; thus, no analysis was conducted on rock contacts for the 6-s and 8-s latencies.

7.6 Workload

Workload is commonly defined as the difference between cognitive demands of a particular job or task and the operator's attention resources [4]. The workload for this study was measured using the six dimensions of mental workload of the NASA-TLX and was used to calculate the overall workload as well. Operators rated their workload at the end of each communication delay condition. Definitions of the NASA-TLX scales were read to the operators before they completed the NASA-TLX questionnaire. A sheet of these definitions was always available for reference to the operator. To aid in understanding how the NASA-TLX scores are interpretated, the evaluators used the interpretation score of NASA-TLX table developed by Hancock and Meshkati (1988) [13] and Prabaswari, Basumerta and Utomo (2018) [14] (Table 15).

Table 15. *The Interpretation Score Table of the NASA-TLX*

Workload	Value
Low	0-9
Medium	10-29
Somewhat High	30-49
High	50-79
Very High	80-100

In a control sequence, such as driving a rover, time-delay may cause some undesirable performance impact [15]. This necessitates that there is a delay between the time in which a command is given to the vehicle, the time this is received by the vehicle, and the time after which the desired action is completed [16]. In situations such as remote driving the LTV on the lunar surface, a time-delay in the order of seconds can readily result in a dangerous state where the roving vehicle is either damage or loss compromising the entire mission. Understanding the effects of time-delay on the operator's performance is a must in terms of motor control [17] [18] and cognition [19] [20].

7.6.1 Workload Results for 0-s and 4-s Latencies

For this study, the overall test operators' workload was *high* with an average of 54% for the 0-s latency condition and 68% in the 4-s latency condition (Figure 27). When examining the mental workload, an analysis of variance showed that the effect of a 4-s communication delay on the operator's mental workload was significant, $F(13, 98) = 2.965$, $p = .001$ when compared to the operator's mental workload in the 0-s communication delay condition.

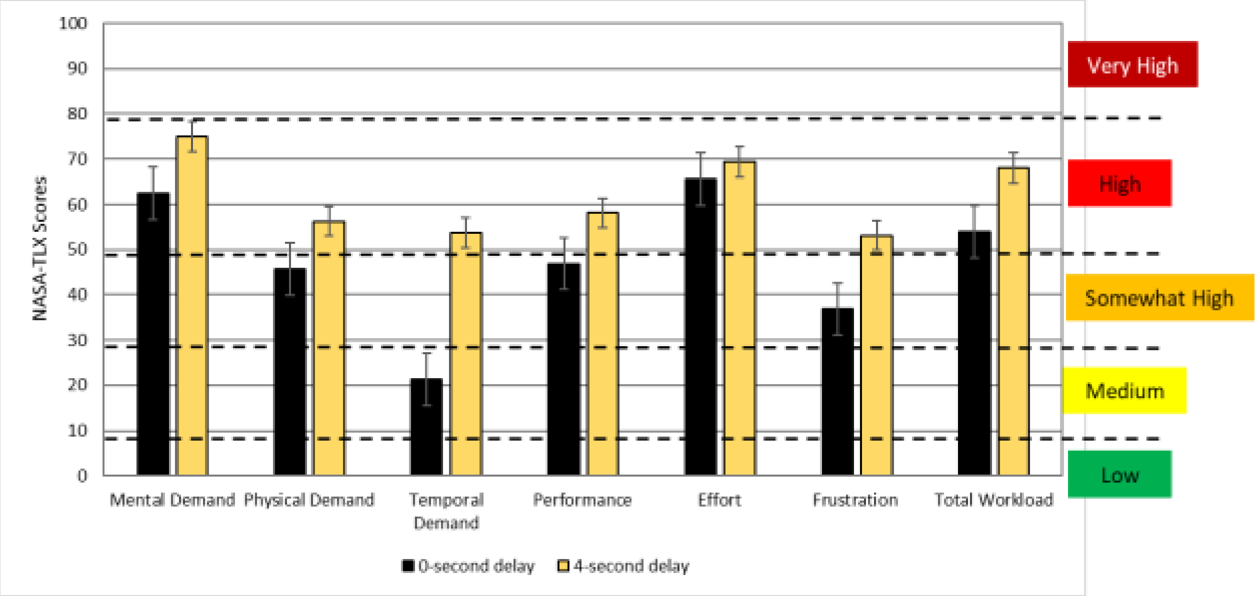


Figure 27. Average workload scores across 0-s and 4-s communication delay conditions.

The major dimensions contributing to the total workload were mental demand and effort as these two had the highest scoring dimensions of the NASA-TLX in both communication delay conditions. Mental demand is defined by the NASA-TLX as how much mental and perceptual activity was required to accomplish the task. Examples of mental demand include thinking, deciding, calculating, remembering, looking, or searching. Effort is described as how hard did the operator have to work (both mentally and physically) to accomplish their level of performance. On average, participants mental demand in the 0-s latency was considered *high* (*M* = 63), while the same operators in the 4-s latency condition was also considered *high* (*M* = 75). Operators stated that while in the 0-s latency condition, factors that impacted their mental demand included being challenged to constantly focus on the vehicle direction and speed, avoiding craters and rocks, shadowed lighting conditions all while trying to safely drive the vehicle without damaging it and staying on course. An additional factor effects their mental demand was splitting their time between the navigation display which included an elevation map and the rover display with the camera view and vehicle telemetry. Factors that provoked a high Effort score (*M* = 66 *high*), which is a combination of mental demand and physical demand, in addition to the mental demand factors previously descripted centered around the physical demand (*M* = 46 *somewhat high*) of the joystick style hand controller and the twisting action that was needed to turn the vehicle (Figure 28). Several subjects reported wrist flexion fatigue that resulted in muscle and hand soreness. Performance also attributed to the overall 0-s latency workload.

Figure 28. Operators noted the awkward twisting motion of the controller cause wrist flexion fatigue.

In the 4-s latency condition, mental demand (*M* = 75) rose twelve points amongst operators. The main factor was having to learn how to adapt to a four second delay which required more intense focus when compared to the 0-s delay condition. This was noted especially when turning to avoid obstacles was required. The wait time to see the results of one's commands to the vehicle to decide what action was needed next and having to project where the vehicle would stop or where turns needed to be attempted. A few operators noted they felt less mental demand as they began to trust the navigational map and rover capabilities which gave them more time to focus on how to provide the input commands to the vehicle. Frustration was also noted as a factor for operators in the 4-s latency configuration. Many stated the frustration was driven by the discrepancy between the behavior of turning and driving functions. The act of turning included a delay in the wheels to rotate in the desired turning direction from a straightforward direction, then actually turning the vehicle, then rotation of the wheels back to the straightforward direction. However, when operators put the vehicle in cruise control using a constant speed, turning became more predictable. Steep hills coupled with low traction was especially difficult since tracking the momentum and slippage over a time-delay was challenging. Reacting to a slip was nearly impossible. Additionally, factors effecting the overall 4-s latency condition included temporal demand and performance.

The major take aways of workload on remote operators is a 4-s communication delay significantly affected the workload. Regardless of communication delay, mental demand and effort were leading factors affecting overall workload. However, in the 4-s latency, frustration also played a role in affecting the operator's workload. To help reduce some of the physical demand connected to effort, remapping and/or a different hand controller would help in the reduction. Additionally, some operators noted that using cruise control in either delay reduces workload as the speed element is offloaded so the operator can put more attention onto avoidance. Furthermore, having a two-person ream reduced operator workload as well (Figure 29).

Figure 29. A two-person team reduces the operator's' workload.

7.6.2 Workload Results for 6-s and 8-s Latencies

In situations such as remote driving the LTV on the lunar surface, a time-delay in the order of seconds can readily result in a dangerous state where the roving vehicle is either damage or loss compromising the entire mission. Understanding the effects of time-delay on the operator's performance is a must in terms of motor control [17] [18] and cognition [19] [20]. For this study, the overall remote operator's workload was *somewhat high* with an average of 37% for the 6-s latency condition; however, in the 8-s latency the operator's workload increased into the *high* range with a 54% overall (Figure 30). When examining the mental workload, an analysis of variance showed that the effect of an 8-s communication delay on the operator's mental workload was significant, $F(13, 41) = 3.593$, $p = .002$ when compared to the operator's mental workload in the 6-s communication delay condition.

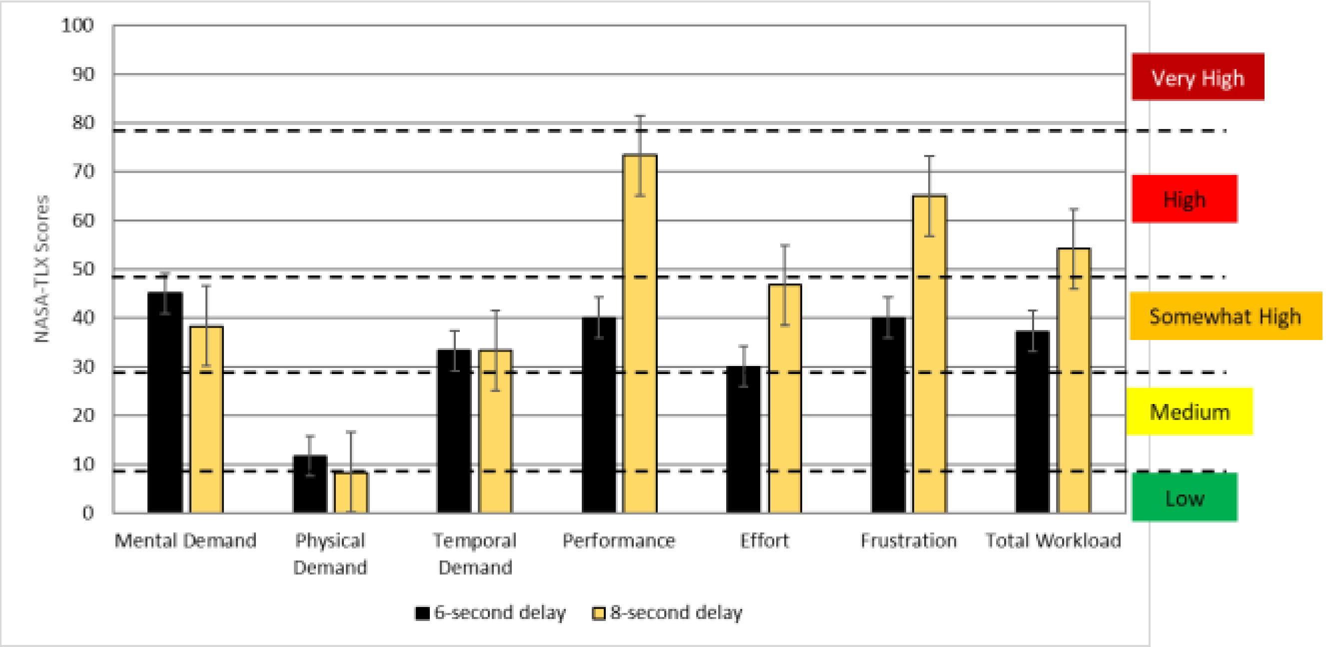


Figure 30. Average workload scores across 6-and 8-s communication latency conditions.

During the 6-s latency driving, the domains which mostly affect the operator's performance was mental demand (*M* = 45), frustration (*M* = 40), and performance (*M* = 40). Even though the remote operator had approximately 3 to 4 hours of training in a 6-second delay environment, they still wanted more training to improve their overall performance and improve confidence. The operators did reveal the workload while in a 6-second delay was much lighter than when operating in an 8-second delay. They noted any speed above 1 m/s (3.6 kph) equated to a lot of over correction in the steering. Stress would increase when remotely driving the vehicle with crew onboard.

For the 8-s latency, the domains which mostly affect the remote operator's cognitive performance was performance (*M* = 73), frustration (*M* = 65), and effort (*M* = 47). As previously denoted in the 6-s latency, the remote operators had the same amount of training for the 8-s latency of 3 to 4 hours; however, the operators considered the workload as doable and having the time latency change from 6 to 8-seconds driving tactics had to adjusted. For example, when the operator flipped the rover during his traverse to the lander, they believe the cause of the incident was the tools in the tool carrier on the back of the rover which made contact with the bottom of the crater and the acting of clipping in 1/6g caused the vehicle to launch into space causing a lot of aerobatics as viewed by MCC and the remote rover operator (Figure 31). In the 8-s latency scenarios, operators revealed the workload was higher due to a significant number of remote operations with longer traverse distances and crew inputs that reduced how successful the remote operator was in accomplishing his performance goals for the task. Operators were trying to operate the vehicle while managing the crews' expectations and avoid terrain features in order to maintain a smooth trajectory. For instance, during Scenario 2A and B, the remote operator overshot the steering of the rover one crater in a crater field and ended up high-centered on a smaller nearby crater rim (Figure 32). At the time of the incident, the crew was walking flanking the rover with an up-sun angle that made seeing the rover difficult. With the rover high centered on the crater rim, the remote operator released the cruise control switched to direct control and briefly gunned the throttle. This did free the rover up from the crater rim; however, with an 8-s latency, the remote operator indicated it was a risky maneuver to any nearby crewmember and at the time EV1 was directly ahead of the vehicle by approximately 4 to 5 meters.

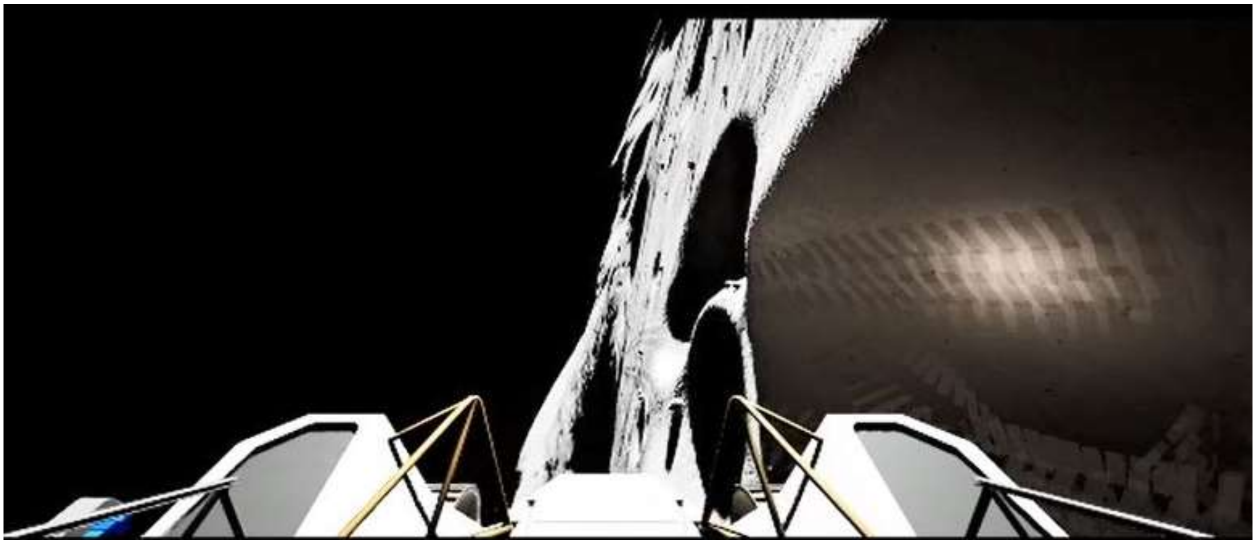


Figure 31. The rover flipping in a crater.

Figure 32. The rover high centered on a crater rim with the crew aiding the remote operator.

7.7 Driving Strategies

A significant factor affecting teleoperated performance is latency [24] whether is originates in the system communications network, sensing hardware, or processing routines. Studies these latency types can negatively impact the performance of a human operator, even in basic remote tasks [24, 25, 26, 27, 28]. To better design s teleoperation systems, understanding how teleoperators interact with robots is key [24].

7.7.1 Driving Strategies Results for 0-s and 4-s Latencies

To further comprehend how a communication delay effects the operator is to identify how the operator strategizes their way of driving the vehicle. In the 0-s delay configuration, the main strategies across all subjects were:

- Driving at a safe and comfortable speed to avoid obstacles as they arose
- Avoid, if feasible, dark shadowed areas with a preference for best lighting to drive
- When in a down-sun situation, use a tacking strategy to improve forward visibility
- Always keep looking ahead for obstacles

When using these 0-s strategies, operators noted judging the rock heights was very deceptive. They noted the natural lighting of the lunar South Pole is tricky. To improve this situation, operators suggested some type of avoidance system, such as a Light Intensification Detection and Ranging device (LIDAR), in combination with their visible view to give a more realistic idea of what lays ahead; however, they did not want to have the visible light as they only source of information to avoid terrain features. Regardless of communication delay, some operators noted they used both the horizontal translation rails and the vehicle fenders as guides to predict a path for the vehicle through heavily concentrated terrain features (Figure 33). As for driving command considerations, the majority of the operators requested having the controller roll function mapped to turning the vehicle with the yaw function being mapped to crabbing the vehicle. Also remapping the camera function on the controller was also suggested. To make camera operations easier, having the zoom capability remapped to the top hat switch and the pan/tilt capability remapped to the castle switch would make the camera operation easier and more useful while driving. As for how the operators use the two displays in their driving strategies, a usage range of 95% to 60% was reported for the rover display, while a range of 40% to 5% was the reported usage range for the navigation display (Figure 34). In the 0-s condition, operators did prefer to use the rover display move for obstacle avoidance, while only noting a general heading from the navigation display. For the navigation display to be more useful, operators indicated a sun/shadow map overlay would aid them in predicting forward visibility. Moving the bubble inclinometer and wheel direction icons to the right side of the navigation screen next to the rover display would improve overall operator display field-of-view for important data. Additionally, using higher contrast screens such as and Organic Light Emitting Diodes (OLED) could improve the camera view aspects.

Figure 33. Operators would use the horizontal bars and fenders as guides.

Figure 34. Display usage range was equal; however, the rover display was more preferred.

The majority of the operators indicated that driving a rover on the lunar surface in a communication delay was difficult. Thus, a number of different driving strategies were recorded. The top six trended driving strategies are as follows in Table 16.

Table 16. *Driving Strategies of Test Operators During Two Communication Delay Conditions*

Communication Delay	Main Strategy	Sub-Strategy Elements
0-s Latency	Drive at safe and comfortable speed to avoid obstacles	If feasible, avoid dark shadowed areas
		Use tacking strategy to improve forward visibility in sun-sun situations
		Always look ahead for obstacles
4-s Latency	Start/Stop	**Start/Stop** Operator inputs command and waits for a response
		Start/Stop/Turn Operator puts in a turn command after stopping then proceeds with Start/Stop
		Start/Stop/Brake Operator inputs a brake command to avoid vehicle slipping on slopes then proceed with Start/Stop
		Start/Stop/Plan Operator stops vehicle and plans next route decision before entering command; then proceeds with Start/Stop
	Blended Command Start/Stop	Operator blends multiple command streams into a single command string making movement more efficient
	Cruise Control and Impulse Control Steering	Set cruise control to a comfortable speed determined by the operator to offload forward speed component Lessens operator mental workload to give them more time react to upcoming terrain and obstructions

While using these driving strategies, operators noted having a command versus refresh rate would be nice to have to inform the operator that the command has been sent and accepted. Suggestions include a change of color for the command or a 4-s timer. To improve the commanding of the vehicle, replacing the current hand controller with something different was suggested. Ideas such a using a shorter controller like the Modular Robotic Vehicle (MRV) controller (Figure 35 and Table 17), arrow buttons, or a game controller would be options to consider. A few operators indicated have specific incremented speed buttons instead of a cruise control function could reduce some of their workload. There was some hesitation in using the crab function due to the induce yaw created by the motor controllers. Usage for the rover display ranged from 95% to 10%, while the navigation display usage ranged from 90% to 5%. This large swing in range could be due in part with some operators more intently focused on the actual view of the terrain to keep the vehicle from harm's way and using the navigation display only for general navigational guidance and not being overly concerned about path accuracy. While others put more trust into the navigation display and less on actual visuals for hazard avoidance.

Figure 35. The MRV joystick.

Table 17. *The MRV Joystick Dimensions*

Element	Dimension (cm)	Dimension (inches)
Controller Length	6.98	2.75
Controller Width	3.81	1.5
Controller Diameter	3.81	1.5

Lastly, most of the operators for this study were a solo act; however, the test team did have an opportunity to collect some data on a two-person driving team. Regardless of communication delay, having a second person accompanying the main driver showed both advantages and some limitations (Figure 36). With a second person, the driver’s workload decreased as they could put focus on driving and avoid obstacles, while the second member took over navigation, became an advisor to the driver and assisted in obstacle avoidance as well. The obstacle avoidance task was split with the driver focused on the far field terrain and the second person focused on the near field terrain. However, a two-person team did take more stationary time for planning purpose which increased their total task time.

Figure 36. A two-person remote operations team.

7.7.2 Driving Strategies Results for 6-s and 8-s Latencies

The type of strategy used during the 6-s latency remote operation was the use of cruise control to maintain speed while zooming in on the navigational maps to see what was ahead. Over the course of the study, the driving strategy shifted toward using the predictive circle function, on the navigation display, for 95% of his navigation with occasional spot checks using the camera's 180-degree panning function for ground truthing in terms of boulders and craters locations. Improvements for the camera included a "snap to position" camera preset list as well as a more ratcheted zoom. Currently, the zoom function on the simulated test camera was unpredictable. The operator indicate they used the roll/pitch indicator to check the slopes against the gradient map on the display. One issue the operator observed was not being able to feel the vehicle get pulled around by the terrain and complicates delayed reactionary inputs by removing a sense of position relative to the ground. Another observation made by the remote operator was going in reverse takes too long so pivoting in place and then driving forward seems to save some time (Figure 37).

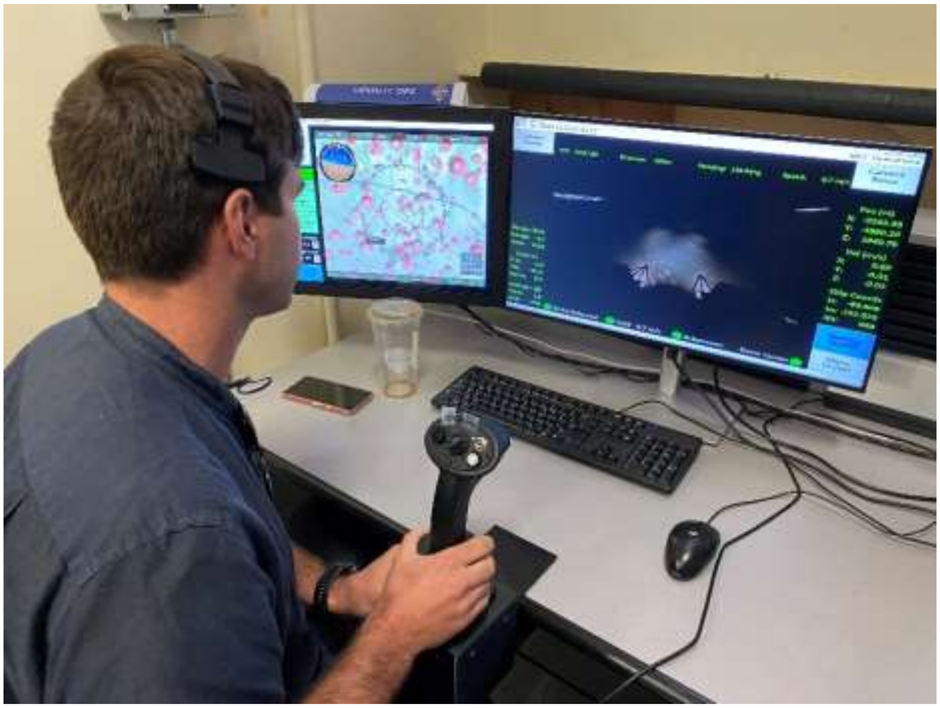


Figure 37. Remote operator in the teleoperation control center.

For the 8-s latency, driving strategies for general operation would have the remote operator set the rover into a low-speed cruise control of approximately 1 to 1.5 kph and plan out turns, using the predicative track circle, approximately 12 seconds in advance to allow for some padding on the turn. Driving performance of the vehicle seemed to be much harder at slower speeds of 0.36 – 0.79 kph; however, the vehicle was more responsive at speeds of 2.88 – 3.60 kph. Driving strategy change with the crew onboard as they have to gauge if the remote operator had inputted a control command versus if had not. Remote operators noted the crew naturally tended towards self-preservation and would use the e-stop if they thought the command to avoid a crater or rock had not been given (Table 18).

Table 18. *Driving Strategies of Remote Operators During Two Communication Latencies*

Communication Delay	Main Strategy	Sub-Strategy Elements
6-Second Latency	Cruise Control	Set cruise control to a comfortable speed determined by the operator to offload forward speed component using the predictive circle function on the display
8-Second Latency	Cruise Control	**General Strategy**: Set cruise control to a comfortable speed determined by the operator to offload forward speed component using the predictive circle function on the display. **Crew Onboard Strategy**: Operator to gauge crew and input control command **Driving Performance for Improve Vehicle Maneuvering:** Cruise Control – 1 to 1.5 kph Responsiveness – 2.88 to 3.60 kph

7.8 Training

Training is an essential part of any space mission. Operators during for the April study had a 15 to 20-minute familiarization session before each communication delay condition to get acquainted with the hand controller, displays, vehicle, and lunar terrain. The training was extended to 3 hours for each latency during the August study. The test team wanted to know if these short training sessions was appropriate for the test and ask the operators how much training would be needed to become proficient for an actual lunar mission. With the minimal training participants received, they thought for a test of this nature, it was enough; however, training for space mission proficiency was another matter. The range of hours needed for lunar teleops proficiency ranged from 20 hours to 100 hours. Most operators noted that a minimal of 30 hours of training was need so that the operator did not feel completely unqualified as to the capabilities of the vehicle. A minimal of 40 hours was suggested for proficiency in remoter operations of a rover in relative clear and flat lunar terrain. For more hazardous environments and complex lighting conditions, a least a 100-hours of training was desired. With this amount of training, the operator would become proficient in all of the vehicle's capabilities in all types of terrain and lighting conditions.

Training strategies differ as well. With the 30-hour training concept, not doing the driving continuously over three 10-hours days, rather break the training up over several weeks so the new operator can think about what took place during that training session. Some operators stated a more intense type of training could be the best approach. Having the new operator would be immerse in driving 10-hours over three days. The program could have the instructor and operator driving the vehicle in a rock yard together on the first day. On day two, the instructor lets the new operator drive independently while the instructor looks over their shoulder. Finally, on day three the new operator is driving the vehicle by themselves without the instructor.

For the longer training programs of three to six months logging a 100-hours or more, subjects noted a shorter starter program of 8 weeks could get a new operator up to 60% proficient with the capabilities of the vehicle and could possibly do certain tasks. Then over the next year, the operator would start blending real-world mission ops to advance their training and become confidence to reach a speed of 5 kph without any hesitation. Thus, overall, the average range of hours at this early stage for operator proficiency is approximately 31 to 43 hours.Table 19 is a summary of training strategies. More study would be required to fully answer the training proficiency question.

Table 19. *Preliminary Estimates of Training Hours for Remote Operator Proficiency*

Hours	Strategy
NA	NA
20-50	Would improve proficiency and speed (Average of 35 hours)
30	10 training sessions to start feeling proficient
40-100	8 weeks of training for 60% proficiency for clear terrain with good lighting Realistic 3 to 6 months for full proficiency for hazardous terrain with questionable lighting (Average of 70 hours)
-	Actual practice on all kinds of real terrain like sandy and rocky terrain to give the operator better instincts.
30	Three full days at JSC Rockyard: Day 1 - Trainee driving with instructor over their shoulder telling them what to do Day 2 - Trainee is driving with instructor nearby Day 3 - Trainee is driving on their own
30	In hour long sessions over a course of a few weeks

Table 19. *Preliminary Estimates of Training Hours for Remote Operator Proficiency*

Hours	Strategy
40	Feeling operator would be able to accept the risk there are dealing with and the possible real damage they could inflict

In situations such as remote driving the LTV on the lunar surface, a time-delay in the order of seconds can readily result in a dangerous state where the roving vehicle is either damage or loss compromising the entire mission. Understanding these effects of the performance on an operator can affect the feasibility of the average kilometers per day an operator can drive the rover which can impact mission planning. The objective of the April study was to examine and provide an average speed of the rover while in a 0-s latency condition and a 4-s latency conditions. In August, the investigative team capitalized on another opportunity to examine two more latencies of 6- to 8-second. The increase in latency time was derived from an analysis of the DSN capabilities. According to the Artemis communication team analysis, the DSN network was not designed for fast bit rate communications. It was originally design for a slower bit rate for distant planetary rovers and satellites. Both studies sought to assure a remote operated roving vehicle can accomplish a 6 to 8 km traverse within a 24-hour period. These studies, taken into account minimal teleoperation experience and training, plus having only one camera view with rover telemetry transmitted through a high bandwidth flawless communications signal with faultless navigation, has shown a very conservative average of four speed variations which achieved the stated distance requirement (LTV-SYS-071) (Table 20).

Table 20. *Average Speeds for Remote Operations of the Lunar Terrain Vehicle For Four Communication Delays*

Communication Delay	Average Speed (kph) across all test conditions	Distance (km)	Time (hh:mm:ss)
0-Second Latency	3.24	6 [a]	1:51:07
		8 [a]	2:28:09
		20 [b]	6:10:22
4-Second Latency	2.56	6	2:20:38
		8	3:07:30
		20	7:48:45
6-Second Latency	2.03	6	2:57:20
		8	3:56:27
		20	9:51:08
8-Second Latency	1.76	6	3:24:33
		8	4:32:44
		20	11:21:49

Note[a]: LTV-SYS-071 6km (threshold), 8km (goal) distance in one 24-hour period when operated remotely
Note[b]: LTV-SYS-029 no less than 20km without stopping for recharge

The average moving time and stationery time were calculated across all conditions and operators and generally shows the time as increasing as the latency increases. One exception is the stationary time in the 6-s latency is higher when compared to the 8-s latency. This is due to part by the inactivity of the remote operation during Scenario 3a and b as the crew opted to drive the vehicle during most of the traverse The average distance was calculated across all conditions and operators (Table 21).

Brake usage also increased as latency increased, especially the use of the e-brake during the special crew mission maneuvers with a remotely controlled vehicle.

Table 21. *Timing and Distance Data Across Both Teleoperation Studies Across Four Communication Latencies*

	0-seconds			4-seconds			6-seconds			8-seconds		
	Moving Time (seconds)	Stationary Time (seconds)	Distance (meters)	Moving Time (seconds)	Stationary Time (seconds)	Distance (meters)	Moving Time (seconds)	Stationary Time (seconds)	Distance (meters)	Moving Time (seconds)	Stationary Time (seconds)	Distance (meters)
Mean	**310.96**	**68.92**	**331.67**	**374.26**	**190.29**	**317.14**	**1047.00**	**2595.67**	**596.60**	**1720.33**	**1016.67**	**872.37**
Standard Error	26.23	8.74	20.96	28.86	26.32	15.57	474.05	1658.66	264.63	538.96	254.98	91.29
Standard Deviation	181.74	60.53	145.24	199.98	182.34	107.88	821.10	2872.88	458.55	933.50	441.63	158.13
Minimum	0.00	0.00	0.00	132.00	0.00	165.34	188.00	555.00	67.80	649.00	664.00	721.40
Median	303.00	51.35	357.00	310.05	115.25	312.97	1129.00	1351.00	842.00	2153.00	874.00	858.90
Maximum	726.50	251.70	534.76	1217.60	761.10	578.64	1824.00	5881.00	880.00	2359.00	11512.00	1036.80

Affecting all of these objective aspects is the human operator. During the April study, it was observed that operating in a 4-s latency significantly increased the total workload of the operator when compared to a 0-s latency. The major factor affecting the operator's workload was mental demand. The wait time to see the results of one's commands to the vehicle to decide what action was needed next and having to project where the vehicle would stop or where turns needed to be attempted required more calculation concentration when compared to the 0-s delay situation. However, two out of eight subjects used cruise control to offload the speed component of operation a rover during the 4-s delay situation which decreased their workload and provided them more time to react to obstacle avoidance. Having a two-person operations team also lessen the workload. However, in the 6-s and 8-s latencies, there was a significant increase in operator workload while in the 8-s condition when compared to the 6-s condition. The major domains affecting the operator's workload while working with an 8-second delay was performance, frustration, and effort. Operators revealed the workload was higher due to a significant number of remote operations with longer traverse distances and crew inputs that reduced how successful the remote operator was in accomplishing his performance goals for the task. Operators were trying to operate the vehicle while managing the crews' expectations and avoid terrain features in order to maintain a smooth trajectory. Conversely, the domains affecting the operator in a 6-s latency was mental demand, frustration and performance. With approximately 3 to 4 hours of training in a 6-second delay environment, operators still wanted more training to improve their overall performance and confidence. They noted any speed above 3.6 kph equated to a lot of over correction in the steering. Stress would increase when remotely driving the vehicle with crew onboard.

Driving strategies in the 0-s latency did not differ much from operator to operator; however, in the 4-s latency situation a minimum of three strategies were identified with some variations among strategies (Table 22). While in a 6-s or 8-s latency, the operator use of the cruise control to maintain speed was more apparent. Additionally, over the course of the August study, the operator took advantage of the predictive circle indicator on the navigation display and over 95% of the operator's navigation used the mask camera 180-degree panning function for ground truthing in terms of boulders and craters. Furthermore, during the 8-s latency, operators started to define more specific parameters in driving strategies for general operations. This consisted of setting the vehicle into a low-speed cruise mode of approximately 1 to 1.5 kph and noticing driving performance of the vehicle seemed to be much harder at slower speeds of.36 – 0.79 kph; however, the vehicle was more responsive at speeds of 2.88 – 3.60 kph. Regardless of communication delay, operators used both the horizontal translation rails and the vehicle fenders as guides to predict a path for the vehicle through heavily concentrated terrain features.

Table 22. *Driving Strategies of Remote Operators During Four Communication Latencies*

Communication Delay	Main Strategy	Sub-Strategy Elements
0-Second Latency	Drive at safe and comfortable speed to avoid obstacles	If feasible, avoid dark shadowed areas
		Use tacking strategy to improve forward visibility in sun-sun situations
		Always look ahead for obstacles
4-Second Latency	Start/Stop	**Start/Stop** Operator inputs command and waits for a response
		Start/Stop/Turn Operator puts in a turn command after stopping then proceeds with Start/Stop
		Start/Stop/Brake Operator inputs a brake command to avoid vehicle slipping on slopes then proceed with Start/Stop
		Start/Stop/Plan Operator stops vehicle and plans next route decision before entering command; then proceeds with Start/Stop
	Blended Command Start/Stop	Operator blends multiple command streams into a single command string making movement more efficient
	Cruise Control and Impulse Control Steering	Set cruise control to a comfortable speed determined by the operator to offload forward speed component Lessens operator mental workload to give them more time react to upcoming terrain and obstructions
6-Second Latency	Cruise Control	Set cruise control to a comfortable speed determined by the operator to offload forward speed component using the predictive circle function on the display
8-Second Latency	Cruise Control	**General Strategy**: Set cruise control to a comfortable speed determined by the operator to offload forward speed component using the predictive circle function on the display. **Crew Onboard Strategy**: Operator to gauge crew and input control command **Driving Performance for Improve Vehicle Maneuvering:** Cruise Control – 1 to 1.5 kph (0.27 – 0.42 m/s) Responsiveness – 2.88 to 3.60 kph (0.8 – 1.0 m/s)

Lastly, in order to make an operator proficient in lunar surface teleoperations, a wide range of training strategies and hours were suggested. Training hours ranged from 20 to 100 hours while strategies included immersion training over a 3-day period, to a short 8-week starter program to get an operator at 60% proficient to do certain tasks, to a yearlong program for proficient in all terrain types and lighting conditions (Table 23).

Table 23. *Preliminary Estimates of Training Hours for Remote Operator Proficiency*

Hours	Strategy
NA	NA
20-50	Would improve proficiency and speed (Average of 35 hours)
30	10 training sessions to start feeling proficient

Table 23. *Preliminary Estimates of Training Hours for Remote Operator Proficiency*

Hours	Strategy
40-100	8 weeks of training for 60% proficiency for clear terrain with good lighting Realistic 3 to 6 months for full proficiency for hazardous terrain with questionable lighting (Average of 70 hours)
0	Actual practice on all kinds of real terrain like sandy and rocky terrain to give the operator better instincts.
30	Three full days at JSC Rockyard: Day 1 - Trainee driving with instructor over their shoulder telling them what to do Day 2 - Trainee is driving with instructor nearby Day 3 - Trainee is driving on their own
30	In hour long sessions over a course of a few weeks
40	Feeling operator would be able to accept the risk there are dealing with and the possible real damage they could inflict

Teleoperations is a combination of elements affecting each other. Speed, distance, time, brake usage and rock contacts are all affected by operator workload, driving strategies, workstation ergonomics and training. This study was an analysis to provide a "first-look" answer to a system requirement; however, ample general knowledge was gained to begin to understand what it will take to make a successful teleoperation lunar operator.

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