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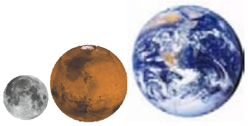
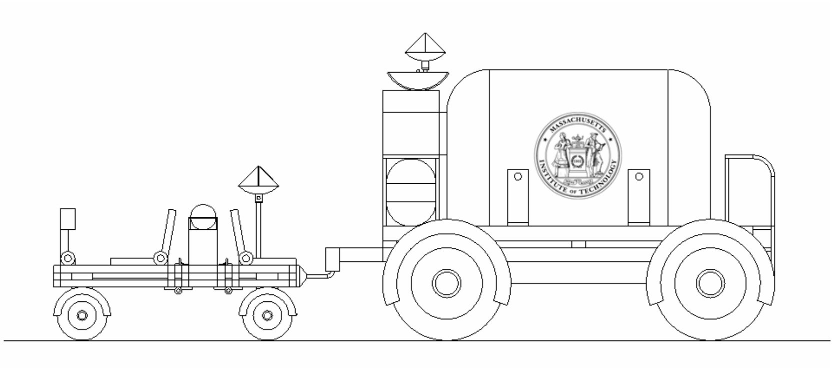
Extensible Planetary Surface Mobility Systems





Final Report

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Executive Summary

1. Introduction

1.1 Design challenge

The MIT 16.89 / ESD 352 space systems engineering course covers the fundamentals of systems engineering and architecting through lectures, and applies these fundamentals in a space system design study. This year's design effort focused on crewed surface mobility systems for the Moon, Mars, and analog sites on Earth, supporting the Vision for Space Exploration (VSE).

The VSE calls for human exploration of the Moon, preparing the way for human Mars missions. Figure 1 overviews NASA's development and exploration roadmap as of 2005. In this plan, lunar exploration begins with robotic orbital and surface missions while crewed vehicles are developed. Crewed missions to the Moon would begin with so-called sortie missions operationally similar to the Apollo J-type missions, with multiple EVAs and geologic excursions from the lander. Subsequent missions would build up a permanently occupied outpost similar to Antarctic research stations. Later missions would begin Mars development, beginning around 2030, using conjunction-class trajectories to provide surface stays of 500-600 days.

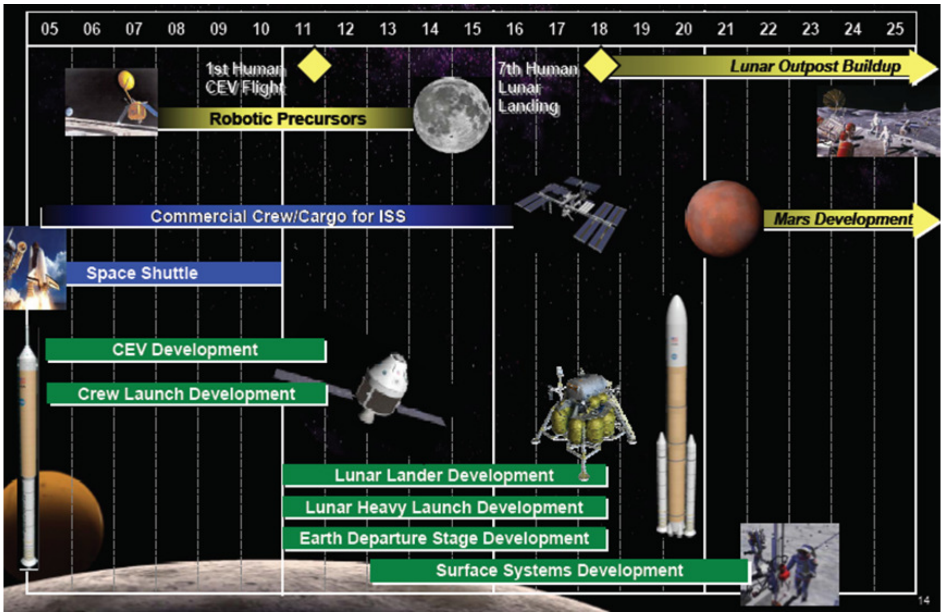


Figure 1: Strategic roadmap for the Vision for Space Exploration, NASA, 2005

Surface mobility systems will play a critical role in effective lunar and Mars surface exploration, because they extend the reach of the crew beyond walking distance (< 5 km) from the outpost or lander, greatly increase the speed of surface mobility, and provide capability to move equipment, experiments and supplies. For long-duration stays on the Moon and Mars, pressurized mobility systems can extend surface excursions beyond the duration of regular EVAs, thereby extending the range of crew exploration from 20-30 km to more than 100 km, and greatly enhancing the return value of such a mission.

Our design study builds upon a large number of previous analyses for lunar and Martian surface mobility systems, emphasizing potential gains achievable through platform commonality. While previous studies have generally focused on point designs for specific operating environments, our study considers a fleet of pressurized and unpressurized vehicles for the Moon, Mars, and Earth analog sites, using common elements to reduce costs and facilitate testing. The class received the following challenge:

> ***"This year's 16.89/ESD.352 Space Systems Engineering class will engage in the question of how to best architect and design a future, extensible planetary surface transportation system. The system will be designed for the Moon with considerations for eventual adaptation to Mars. In addition, the class will consider how a terrestrial version of the lunar transportation system can be built for testing in lunar and Mars analog sites on the Earth."***

1.2 Analysis and Design Approach

The class began with a systematic analysis of Moon and Mars mobility requirements and architectures, then developed subsystem-level design for a single preferred architecture. The design model provides end-to-end mapping from environment parameters to system parameters to operational capabilities. Design effort concentrated most heavily on lunar vehicles, providing a detailed baseline from which differences in Earth and Mars systems can be inferred.

The remaining chapters of the report follow the approach the class took to addressing the extensible surface mobility design challenge:

- **Chapter 2, Mobility System Requirements Analysis**, examines value-delivering activities on the lunar surface to understand how value can be delivered by a planetary surface mobility system for human exploration. We present a formal problem statement capturing beneficiaries, operands, intent, operating processes and system form. Specific value-delivering processes are grouped into 4 design reference missions (DRM) based on their relationships to one another. The problem statement and DRMs provide the basis for Level 1 and Level 2 requirements.

- **Chapter 3, Mobility System Architecture Analysis**, documents analysis of surface mobility architectures following the requirements in Chapter 2. We quantitatively analyze a large number of mobility architectures, accounting for failure modes and associated walk-back / drive-back constraints for crew safety. Architectures are evaluated according to cumulative performance and mass. Using a reference design, we conduct a sensitivity analysis for parameters held constant in the architecture analysis, providing the basis for an informed architecture selection.

- **Chapter 4, Mobility System Design**, overviews the detailed vehicle design effort for a lunar mobility system carried out based on the final architecture selection. This effort used a linked array of parametric models to size subsystems for a baseline design, which was subsequently detailed with geometric layout, and analyzed for operational performance. This chapter constitutes Part 1 of our answer to the design challenge.

- **Chapter 5, Integrated Dynamic Capability Analysis**, overviews the integrated capability analysis framework MUSE used to analyze operational performance, with sample results for a few specific locations on the Moon.

- **Chapter 6, Commonality with Earth and Mars Mobility Systems**, describes the commonality analysis carried out during and after the detailed lunar vehicle design. This analysis investigated the sensitivity of subsystems to changes in the planetary environment, and identified identical, related, and custom elements required to extend the lunar design to a platform providing Earth, Moon, and Mars capabilities. The commonality analysis constitutes Part 2 of our answer to the design challenge.

- **Chapter 7, Summary and Conclusions**, summarizes the design effort and results documented in this report.

- **Chapter 8, Acknowledgements**, recognizes those people who contributed to the class through lectures, design reviews, design participation, and general advice.

- **Chapter 9, References**, lists sources cited throughout the report.

- **Chapter 10, Appendices**, provides a wealth of backup information related to various sections in the report.

2. Mobility System Requirements Analysis

Designing a planetary mobility system platform extending across multiple decades and multiple environments requires a thorough understanding of the stakeholders of the system, and how it delivers value to these stakeholders. Our analysis of the value delivery mechanism provides the basis for top-level requirements that flow down to Level 1 and Level 2 requirements through analysis of system context and use cases.

2.1 Problem Statement

Early on, the class brainstormed processes and activities that deliver value on a planetary surface. Based on this survey, the activities that require a surface mobility system (pressurized and unpressurized) were distilled and documented. The OPM diagram in Figure 2 shows the result of this analysis:

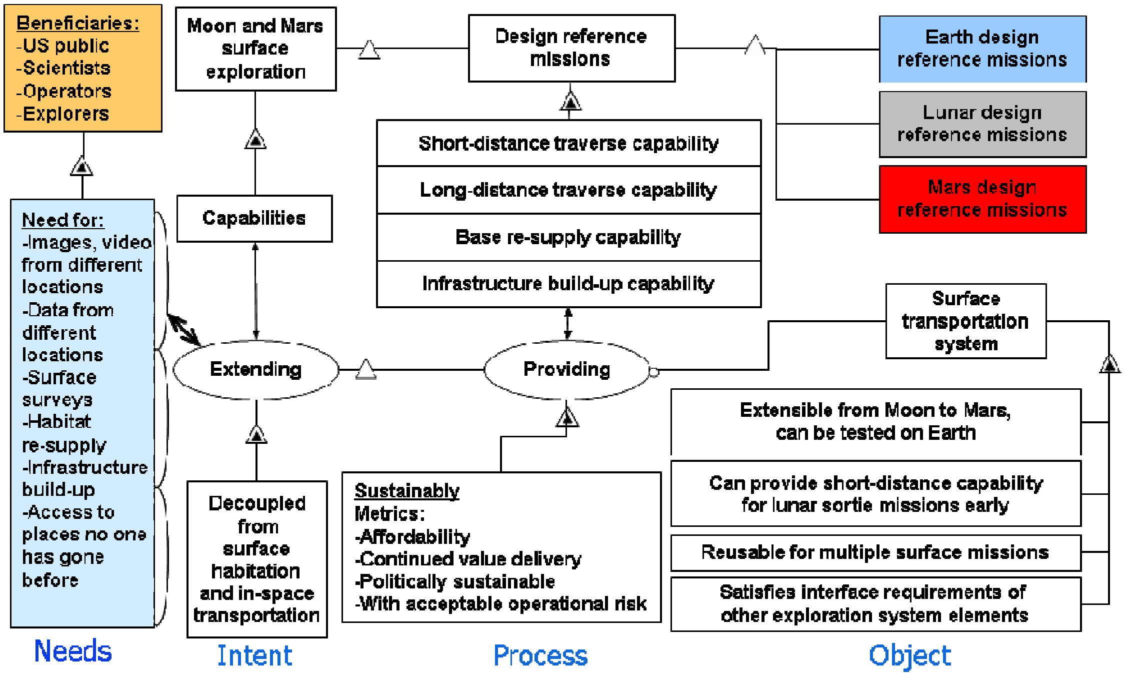


Figure 2: OPM view of the high-level surface mobility system architecture focused on value-delivery

The primary beneficiaries of Moon and Mars surface exploration are scientists (acquire data), explorers (access new locations), operators (gain experience), and the American public (enjoy "armchair exploration" and sharpen interest in science and engineering). The specific benefits of these groups can be categorized broadly into information, material, and location:

- Images, video, and data transmitted back to Earth
- Permanent goods delivered to the lunar surface, and samples delivered back from the lunar surface
- Access to locations and sites that yield valuable data or samples, or have never been explored before

The planetary surface mobility system satisfies these needs by providing capability to conduct short-range and long-range excursions, to transport supplies from a lander to an outpost, and to construct outposts and supporting infrastructure. The primary measures of effectiveness for the mobility system were cost and performance; mass was used as a proxy for cost.

The class made an early decision to exclude outpost interfaces and elements from our design scope in order to enable more detailed analysis and design of the mobility system itself. Therefore, the mobility system was considered decoupled from the outpost, and we made no attempt to optimize combined characteristics of outpost and mobility systems, nor to consider architectures not involving an outpost or lander.

Several important attributes of the mobility system followed immediately from the design challenge and value analysis:

- The mobility system must be extensible from the Moon to Mars, and a modified version must be testable on Earth
- The mobility system must provide short-range exploration capability for lunar sortie missions
- The mobility system must be reusable over several surface missions; investment in a new mobility system for each surface mission is not practical
- The mobility system must satisfy the interface requirements of other outpost elements; a context analysis identified these requirements in detail (see below).

Based on Figure 2, the class generated a formal problem statement that served as a guideline for further requirements and architecture analysis and design:

The goal of the surface mobility system is

- ***<u>To</u> extend the capabilities of Moon and Mars surface exploration***
- ***<u>By</u> providing the capabilities to carry out 4 types of design reference missions on the Moon, Mars, and in analog environments on Earth***
    - ***Short-distance excursions (unpressurized)***
    - ***Long-distance excursions (separate pressurized capability)***
    - ***Base-re-supply excursions (cargo transport)***
    - ***Infrastructure build-up missions (cargo delivery, moving of resources, etc.)***
- ***In a sustainable way (metrics)***
    - ***Affordably***
    - ***Providing continued value delivery***
    - ***With acceptable development and operational risk (especially to human life)***
    - ***Policy robust***
- ***<u>Using</u> a surface transportation system which***
    - ***Is extensible from Moon to Mars, and can be tested on Earth***
    - ***Can provide short-distance capability for lunar sortie missions early***
    - ***Is reusable for multiple surface missions***
    - ***Can successfully interface with other exploration system elements (such as habitats, communications equipment, electrical power system, etc.)***

2.2 Design Reference Missions

The class outlined four Design Reference Missions (DRMs) used to evaluate our architectural choices. The DRMs were designed to cover the broad range of operational tasks that astronauts would perform on the Earth, Moon, and Mars. Table 1 summarizes the where each of the DRMs are performed.

	DRM 1	DRM 2	DRM 3	DRM 4
	short traverse	long traverse	resupply logistics	infrastructure operations
Earth Analogue	✓	✓	✓	✓
Lunar Sortie	✓	✗	✗	✗
Lunar Outpost	✓	✓	✓	✓
Mars Outpost	✓	✓	✗	✓

Table 1: DRM Applicability Matrix

Sortie missions refer to short surface stays (up to one week) on the surface of the Moon, during which astronauts live in the lunar lander. Sortie missions cannot be performed on Mars, since Mars expeditions will be much longer due to trajectory constraints.

Outpost missions will occur on both the Moon and Mars, in which astronauts will live in a habitation module that is part of a pre-placed outpost encampment. A typical Moon mission may last up to 180 days, while typical Mars missions will last ~600 days [CE&R].

DRM-1: Short Distance Excursion

Short distance excursions will explore the immediate vicinity around the LSAM or outpost, similar to the Apollo 15-17 excursions using the LRV. Astronauts performing a DRM-1 would wear space suits, and not make use of pressurized mobility elements. Primary DRM-1 tasks include:

1. *Geological survey*
   General science investigation of local sites of interest and surveying of the immediate vicinity, including scouting, photo/video documentation, and some sample collection.
2. *Deployment of science instruments*
   Similar to the ALSEP packages on the Apollo missions, astronauts can deploy surface science instruments near the base.
3. *Investigation of primary science sites*
   The LSAM / outpost will likely be situated near several scientific sites of interest, allowing astronauts to use the mobility system to travel to a science site to conduct detailed surveys and sample collection, including sub-surface drilling.

Duration and Range

The duration of a DRM-1 excursion is limited by space suit life support capacity and astronaut fatigue, nominally assumed 8 hours based on current space suit technology. To determine the range of a DRM-1, we investigated Apollo 15-17 traverses and found that astronauts reached a maximum distance (radius) from the LEM of ~11 km [Surface Journal]. This constraint was observed so that if the LRV failed, the astronauts would be able to walk back to the LEM. Since the proposed lunar missions are longer and carry more crew, we expect that the desired exploration area would be increased, and so also the maximum distance from the outpost.

Safety

At a distance of 20 km from the base, astronauts are unlikely to have sufficient suit life support capacity to walk back to base if their mobility system fails. We consider two contingency solutions: First, they could use multiple vehicles during a DRM-1 excursion, and in an emergency the astronauts on the failed vehicle could “piggy-back” on the remaining vehicle(s) to return to base. Second, supply caches could be left at various points during the excursion to be used if astronauts were forced to walk back to base.

DRM-2: Long Distance Excursion

Unlike short-distance excursions, long-distance excursions use a pressurized mobility element to visit sites beyond the range of a single EVA. Astronauts performing a DRM-2 would be equipped with space suits but would doff their suits and live inside the pressurized element between EVA periods.

DRM-2 tasks include those in DRM-1, along with tasks such as eating, sleeping, and washing inside the pressurized element. DRM-2 is only possible during outpost missions, since pressurized mobility elements would not be included onboard an LSAM designated for sortie missions.

Duration and Range

Duration depends primarily on the life support capacity of the pressurized mobility system, making this a design variable. A typical DRM-2 would consist of 2 days to drive to the site of interest, 3 days of exploration in the vicinity of the site, and 2 days to drive back to the outpost, for a total of 7 days. This quantity remains a variable for the architectural selection and detailed design phases.

The desired range of DRM-2 excursions follows from the distribution of science sites on both the Moon and Mars. The ESAS report notes that the major lunar sites of scientific interest are distributed roughly 100 km apart, with minor sites in between [CE&R]. This was used as the upper bound for DRM-2 range: we assume that the outpost would be landed near a major science site, and the astronauts would travel no farther than the next closest major site. For Mars, the Draper/MIT CE&R report distinguishes between major science sites, with an average spacing of 200 km, and “National Parks”, which are clusters of science sites with an average spacing of 4500 km, as shown in Figure 3 [CE&R]. It is unlikely that any practical mobility system will be able to traverse this latter distance, so we assume that the outpost is landed near a National Park, and that the astronauts use the mobility system to get to the nearest major site.

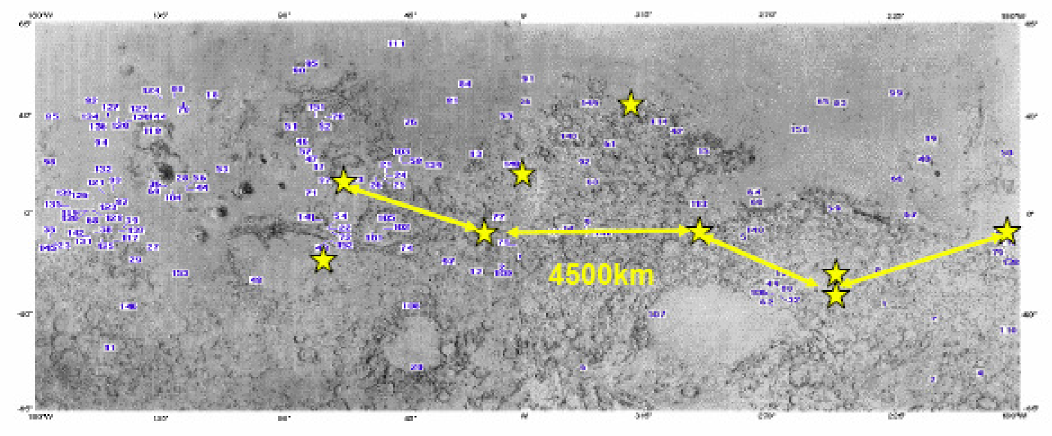


Figure 3: Mars science site distribution

Safety

Astronauts on DRM-2 would not be able to walk back in an emergency, necessitating a multi-vehicle architecture. If an unpressurized element fails, then the astronauts can use other unpressurized elements to either continue the mission or abort and return to the base. If a pressurized element fails, either a duplicate pressurized element must be available that can support all astronauts, or the unpressurized elements must be fast enough to allow the astronauts to drive up to 200 km back to base without re-supply.

DRM-3: Re-supply Logistics

Moon outpost missions may require unpiloted cargo flights from Earth in order to replenish supplies. DRM-3 tasks involve driving to the re-supply lander, loading pallets onto the vehicle, and driving back. The total cargo mass supplied depends on the mission. For example, for a 6-month outpost mission for 4 astronauts, we estimate that a total of 7.3 mt of cargo is required to support the crew, based on logistics models developed by researchers at MIT.

Duration and Range

We do not impose a limit on the total amount of time required for re-supply, but we stipulate that number of *consecutive* EVA hours on DRM-3 does not exceed the capacity of the space suit (8 hours), even if multiple EVAs are required. We assume that the re-supply craft lands in the vicinity of the base. Apollo experience and current technology allows a precision landing within several hundred meters of the target, but the re-supply craft may be required to land up to 2 km away from the outpost to prevent blast effects from damaging outpost structures. This provides a guideline for the range of DRM-3 excursions.

Safety

Since the re-supply craft will land within within a few kilometers of the outpost, astronaut(s) would walk back to base in the event of a vehicle failure.

DRM-4: Infrastructure Operations

A lunar or Mars outpost would require upkeep, maintenance, and infrastructure setup tasks in addition to exploration. Figure 4 shows the ESAS baseline design of a lunar outpost, which involves several large, pre-deployed modules [ESAS]:

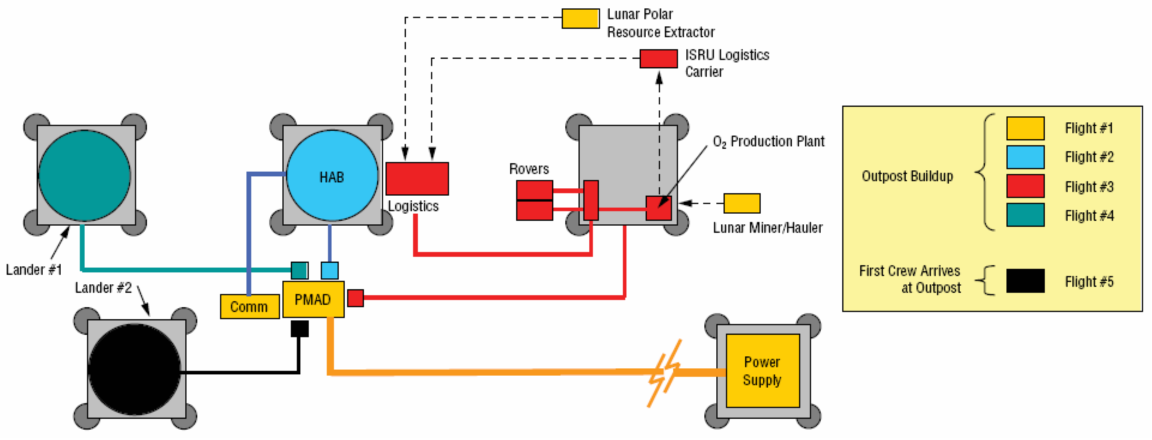


Figure 4: ESAS Outpost Baseline Design

These modules would not be moved or modified, but several tasks would be required to maintain the base and obtain science return in the vicinity of the outpost. These tasks are:

1. *Deployment of science instruments*
   Science packages will be deployed around the base to run experiments and take measurements of the local environment. Experience from Apollo (such as the ALSEP) shows that these packages can be on the order of 10 to 100 kg [Apollo Experiments Catalog].
2. *Transmission cable deployment*
   The outpost will be pre-deployed on multiple robotic landers prior to the arrival of the crew. Although these modules will not require setup, they will require establishing connections between them.
3. *Light surface construction*
   Astronauts could move regolith on a small scale to construct berms for rocket plume / radiation shielding, clear terrain for roadways, or dig trenches for sub-surface investigation. ESAS considers construction activities to be an “evolved” activity, not immediately needed.

Duration and Range

As for DRM-3, we assume that infrastructure operations would be performed using single EVAs without overnight stays away from the outpost. Thus a single DRM-4 EVA does not exceed 8 hours. Also, since all DRM-4 operations are performed in the vicinity of the outpost, astronauts would not range beyond ~5 km from the base.

Safety

Astronauts can walk back to the habitation module if mobility system units fail. Assuming astronauts maintain appropriate time and EVA consumable margins while on

DRM-4, they would always have sufficient life support resources in their space suits to return to the habitat.

References

[CE&R]: Draper/MIT CE&R Study, 2005.

[Surface Journal]: Apollo Lunar Surface Journal,
http://www.hq.nasa.gov/office/pao/History/alsj/frame.html, web pages.

[ESAS]: Exploration Systems Architecture Study. NASA, 2005.

[Apollo Experiments Catalog]: Catalog of Apollo Experiment Operations.
http://www.myspacemuseum.com/apollo.htm, web pages.

2.3 Requirements Flow-Down

Based on the problem statement and the definition of design reference missions, requirements analysis was carried out for defining lower-level requirements essential for system design. Requirements analysis was based on context analysis (see Figure 5) and on review of literature on subsystem requirements and constraints. Figure 6 shows an excerpt from the final level 0 to level 2 requirements table used by the class. The requirements were organized into three groups:

- General requirements capturing crew safety and programmatic issues such as reusability, lunar sortie mission requirements, etc.
- DRM-specific requirements detailing the DRMs
- Interface requirements to other elements of the overall exploration architecture

The full requirements table in spreadsheet form is provided on a CD together with the class documents and models.

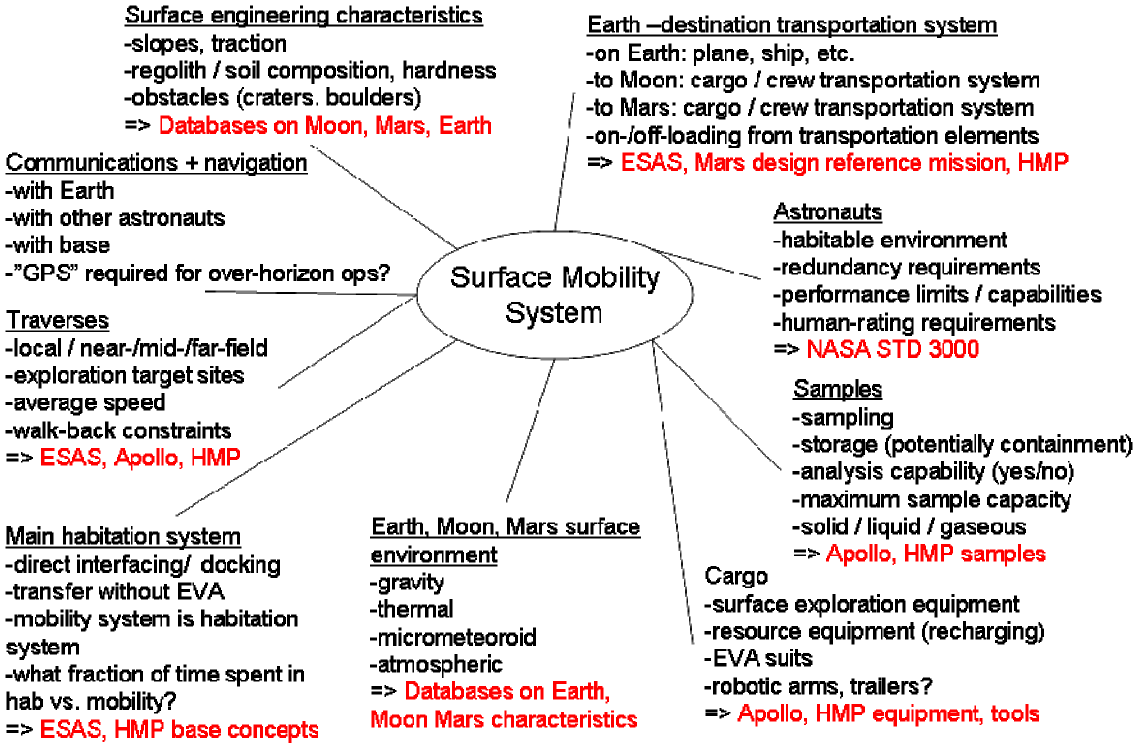
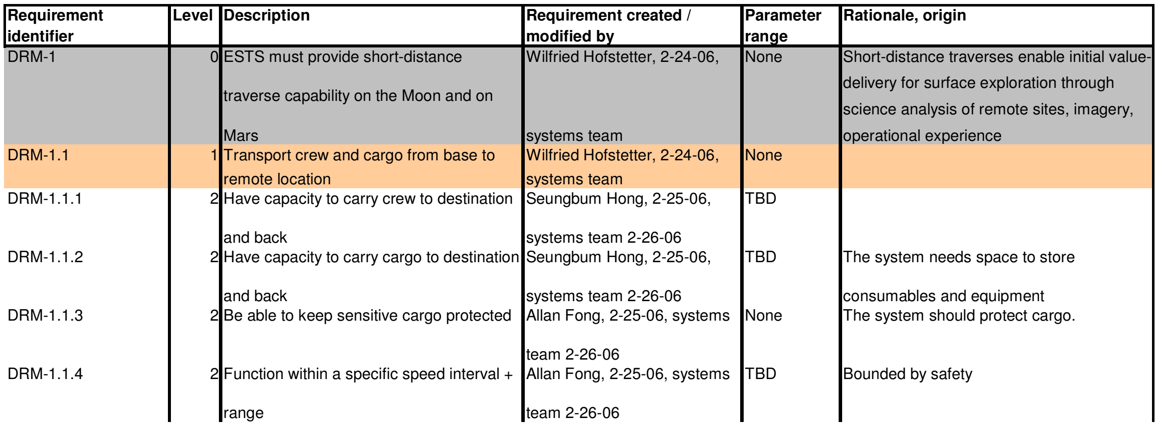


Figure 5: Context analysis for the surface mobility system



Requirement identifier	Level	Description	Requirement created / modified by	Parameter range	Rationale, origin
DRM-1	0	ESTS must provide short-distance traverse capability on the Moon and on Mars	Wilfried Hofstetter, 2-24-06, systems team	None	Short-distance traverses enable initial value-delivery for surface exploration through science analysis of remote sites, imagery, operational experience
DRM-1.1	1	Transport crew and cargo from base to remote location	Wilfried Hofstetter, 2-24-06, systems team	None	
DRM-1.1.1	2	Have capacity to carry crew to destination and back	Seungbum Hong, 2-25-06, systems team 2-26-06	TBD	
DRM-1.1.2	2	Have capacity to carry cargo to destination and back	Seungbum Hong, 2-25-06, systems team 2-26-06	TBD	The system needs space to store consumables and equipment
DRM-1.1.3	2	Be able to keep sensitive cargo protected	Allan Fong, 2-25-06, systems team 2-26-06	None	The system should protect cargo.
DRM-1.1.4	2	Function within a specific speed interval + range	Allan Fong, 2-25-06, systems team 2-26-06	TBD	Bounded by safety

Figure 6: Overview of the requirements table with level 0 (grey), level 1 (orange), and level 2 (white) requirements

3. Mobility System Architecture Analysis

3.1 System Ground Rules and Assumptions

A number of assumptions were made in order to define the architecture analysis. These relate to the mission framework, safety requirements, and other basic concerns.

- Though the system would be used for both exploration and testing on the Earth, Moon and Mars, the architecture analysis was performed based on the Moon and Mars only in order to ensure efficiency in these mass-constrained environments. The same architecture was then used for the Earth-based vehicle, to preserve commonality.

- Initial study suggested that the design and architecture would be driven by DRM-1 and DRM-2 requirements, so DRM-3 and DRM-4 were not included in the architecture analysis.

- The mass and geometry of the system were constrained to be within transportation capabilities for Earth, Moon, and Mars. This included transport limitations faced in delivering the system to remote locations on Earth.

- For safety, it was assumed that the crew would always operate in groups of at least two. This means that for any leg of a traverse, or for any pressurized volume, there would be at least two crew.

- Pressurized mobility assets were required to provide the shielding and life-support necessary to survive a Solar Particle Event (SPE) of reasonable intensity. It was assumed that three hours warning could be provided for such an SPE.

- It was assumed that actual distances traversed on an excursion would average 50% higher than the two-way straight-line distance to the farthest point of the excursion, based on experience from Apollo LRV traverses.

3.2 Metric Analysis

In selecting metrics, we considered cost, vehicle capability, science value, risk, extensibility, and robustness. Mass serves as a proxy for cost, since it drives launch costs and correlates with development costs. Vehicle capability includes attributes such as range, speed, cargo capacity, crew capacity, or terrain performance. Science value can be quantified in several ways, as discussed below. In our analysis, risk, extensibility, and robustness ultimately served as constraints rather than metrics.

The pre-existing surface mobility vehicle model used for the architectural study used the capability parameters mentioned above as inputs to the model and provided mass as an output. Hence mass was used as the cost metric.

In defining a metric for science value, we considered modeling site visitation of actual or assumed geographical distributions of sites of interest, but this approach was deemed too complicated for the architecture analysis. Instead, we assumed a constant time required for science exploration at a single site, and measured the number of sites visited assuming a uniform linear distribution of sites along the traverse path. While simple, this metric ensured an appropriate balance of time spent at each individual site and distance covered to visit several sites. Any time on an excursion not spent driving, loading, or unloading was assumed to be available for science activities. The driving time was calculated by dividing the traverse length by the assumed vehicle speed, and the loading time was calculated according to an assumed constant divided by the number of crew.

$t_{science} = t_{total} - t_{traverse} - t_{loading}$
$t_{traverse} = \text{range/speed}$
$t_{loading} = \text{loading time (crew-hours)} / n_{crew}$
$\# \text{ sites} = \max(t_{science} \times n_{crew} / \text{time per site, number of sites available})$
$\text{number of sites available} = \text{range}/2 \times \text{line density of science sites}$

The architecture analysis attempted to minimize mass and maximize number of science sites visited, within constraints imposed by risk, extensibility, and robustness considerations.

3.3 DRM-1 and DRM-2 Architectures Analysis

3.3.1 DRM-1 Architecture Analysis

The architecture choices for DRM-1 fulfilling the above assumptions and constraints are enumerated in Table 2 and Table 3.

Table 2: Moon DRM-1 Architectures

# of crew in a vehicle	# of crew walking	# of vehicles	# of crew per vehicle
2	2	2	1
4	0	2	2
4	0	4	1

Table 3: Mars DRM-1 Architectures

# of crew in a vehicle	# of crew walking	# of vehicles	# of crew per vehicle
2	4	2	1
3	3	2	1 & 2 *
3	3	3	1
4	2	2	2
4	2	4	1
6	0	2	3
6	0	3	2
6	0	6	1

* The UPV would be designed to hold two people. In this design, though, one of the UPVs would only hold one person, while the other would contain the nominal two person crew.

The flow-down diagram in Figure 7 shows how these options are generated: here the red lines represent Mars, and the black lines represent the Moon.

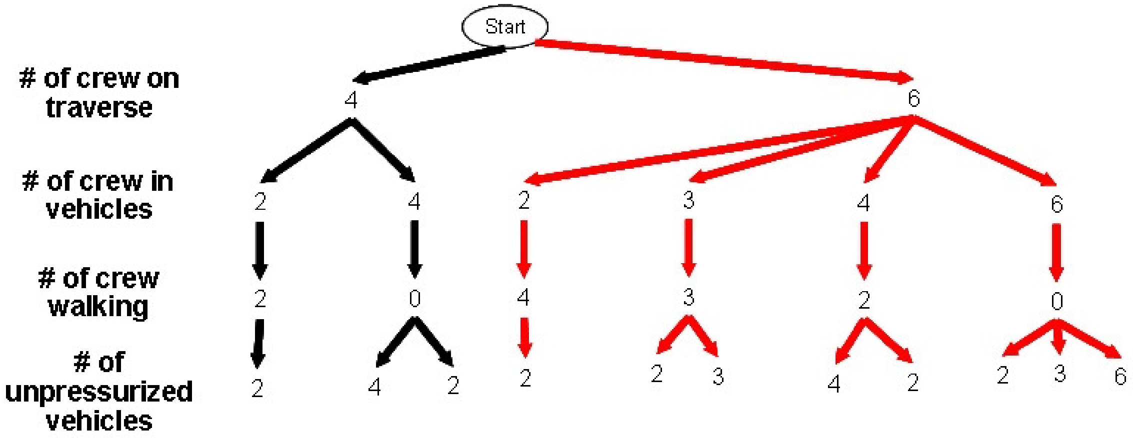


Figure 7: DRM-1 Architecture Options

The independent variables in Table 4 were used for the architecture selection. For this analysis, rather than optimizing the power source internally in the model, we simply generated architecture variants for each type of power source.

Table 4: Independent DRM-1 Variables

Variable name	Range	Units
Speed	10-20	km/hr
Power source	Batteries, fuel cells, solar panels, RTG	n/a

For the lunar sortie mission, it was assumed that there were 5 days of exploration available, so the number of sites from a single DRM-1 excursion was multiplied by 5. Additionally, the power mass for consumable power systems was multiplied by 5, to reflect the need for additional fuel each day, in order to determine the total mass.

Figure 8 shows the tradespace results generated for lunar vehicles, highlighting the Pareto front toward the upper left. The chart for Mars is similar. These charts show that the fewest number of vehicles (2) is preferable for both planets. Depending on mass requirements, the crew may all drive on the vehicles, or two crew members can walk. Fuel cells prove the most preferable power source. The details behind this model are documented in the Appendix.

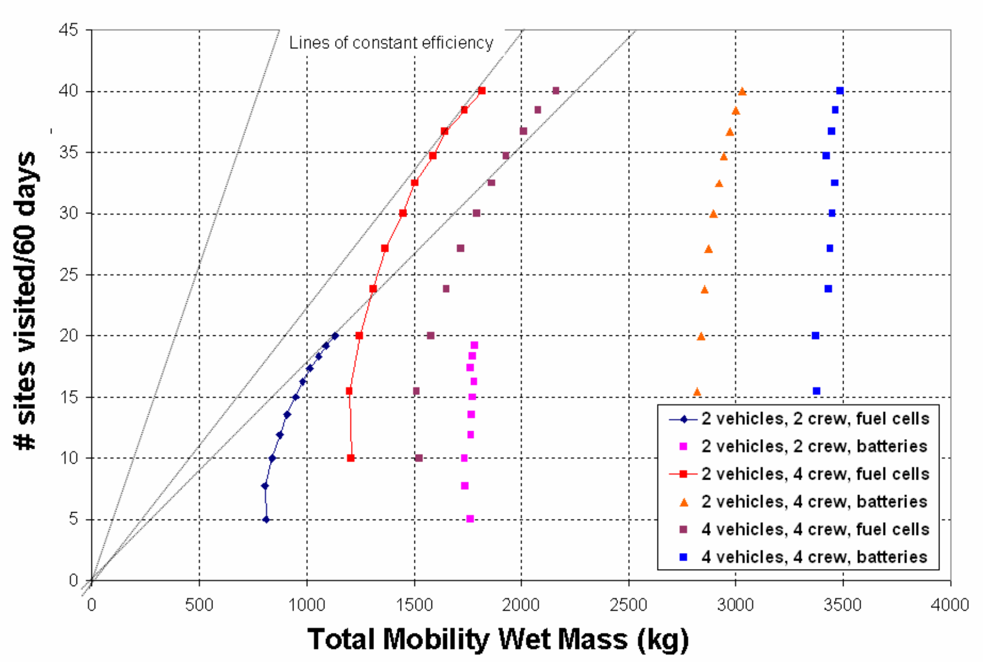


Figure 8: Moon Pareto Front Data

Based on this analysis, the baseline architecture for the lunar DRM-1 is 2 UPVs, each nominally equipped to hold 2 crew. For Mars, with a crew of 6 , this is modified to 2 UPVs each equipped to hold 3 crew, the most efficient option available.

3.3.2 DRM-2 Architecture Analysis

The DRM-2 analysis built on the DRM-1 analysis. For a DRM-2, the pressurized vehicle (whether a camper or a pressurized rover) is supported by multiple unpressurized vehicles. The astronauts use the pressurized vehicle to stay nights away from base, but all science work is accomplished using the unpressurized vehicles. The DRM-2 consists of long driving legs with the pressurized vehicles, punctuated by a series of DRM-1 sorties (Figure 9). In this analysis, the pressurized rover is sized to tow unpressurized vehicles, while the camper is towed by a stronger unpressurized vehicle.

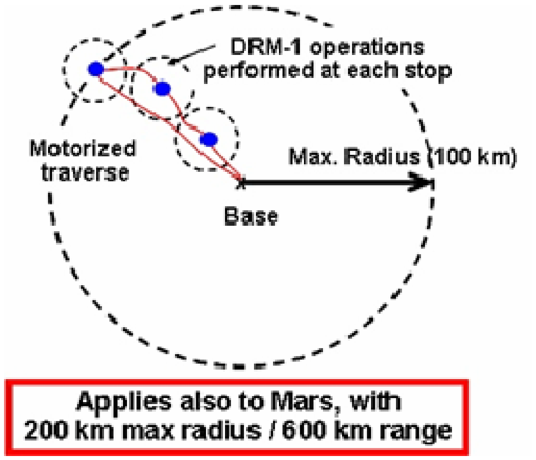


Figure 9: DRM-2 Operations Model

Once again, the safety analysis outlined in Section 3.1 was used to shorten the list of potential architectures to a manageable number. For the pressurized vehicles, no crew member is ever alone for safety reasons. Again, the black lines in Figure 10 represent the Moon, the red lines represent Mars.

Table 5: Moon DRM-2 Architectures

Type of vehicle	# of crew driving	# of vehicles	# of crew per vehicle
Camper	2	1	2
Camper	4	1	4
Camper	4	2	2
Pressurized rover	2	2	2
Pressurized rover	4	2	4
Pressurized rover	4	4	2

Table 6: Mars DRM-2 Architectures

Type of vehicle	# of crew driving	# of vehicles	# of crew per vehicle
Camper	6	1	6
Camper	4	1	4
Camper	2	1	2
Camper	6	2	3
Camper	4	2	2
Camper	6	3	2
Pressurized rover	6	1	6
Pressurized rover	4	1	4
Pressurized rover	2	1	2
Pressurized rover	6	2	3
Pressurized rover	4	2	2
Pressurized rover	6	3	2

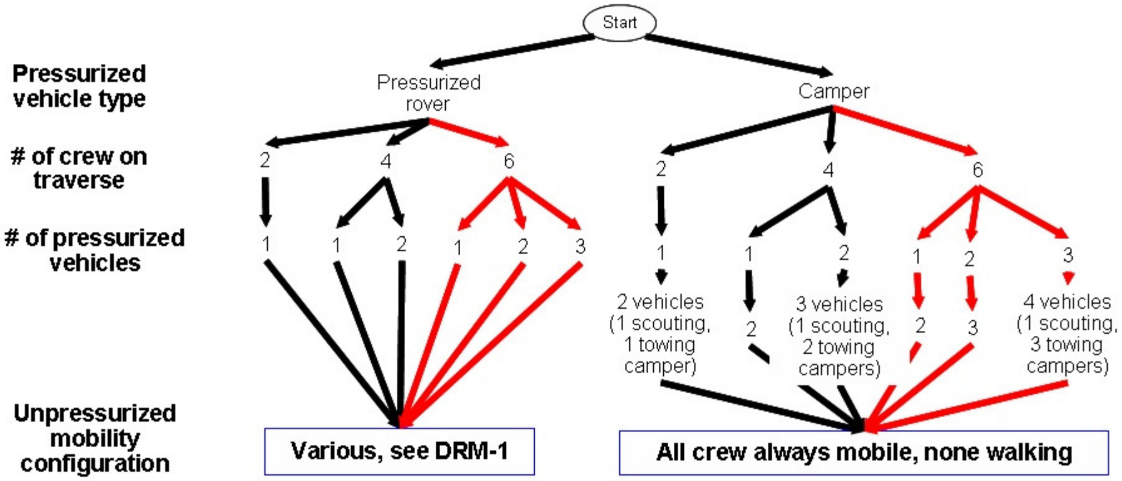


Figure 10: DRM-2 Architecture Choices

Each of these options was tried with all logical configurations of unpressurized vehicles. For instance, 2 UPVs with 3 crew each are not able to tow 3 campers. For the campers, it was assumed one extra vehicle would scout in front of the towed vehicles. Table 7 lists the independent variables in the DRM-2 analysis:

Table 7: DRM-2 Independent Variables

Variable name	Range	Units
UPV option	n/a	n/a
Sortie days	5-10	days
Power source type	Batteries, fuel cells, solar panels, RTG	n/a

In addition to those a series of dependent variables were specified. The dependent variables for the UPVs were the same as specified previously, with some variations. The UPVs for the camper had zero payload mass, but towed the full camper mass. A short list of the variables for the pressurized vehicles is presented in Table 8.

Table 8: DRM-2 Dependent Variables

Variable name	Value	Units
Driving range	300 (Moon) or 600 (Mars)	km
Velocity	15	km/hr
Worst case slope traverse	10	degrees
Number of EVAs	Number of crew * number of sortie days	n/a

The cumulative number of sites was determined by adding the total number of sites visited over a trip of a given duration. The vehicles were then assumed to leave the day after they returned, so the number of sites were added up to the cumulative numbers above (roughly 1/3 of the expected stay for each of the planets: 60 days for the Moon, 180 days for Mars).

Due to the large number of architectural options, the tradespaces shown in Figure 11 and Figure 12 differentiate only the baseline choice (2 campers, 2 crew each) from the other architecture options. A more detailed look at the designs will be conducted in the sensitivity section (Section 3.4).

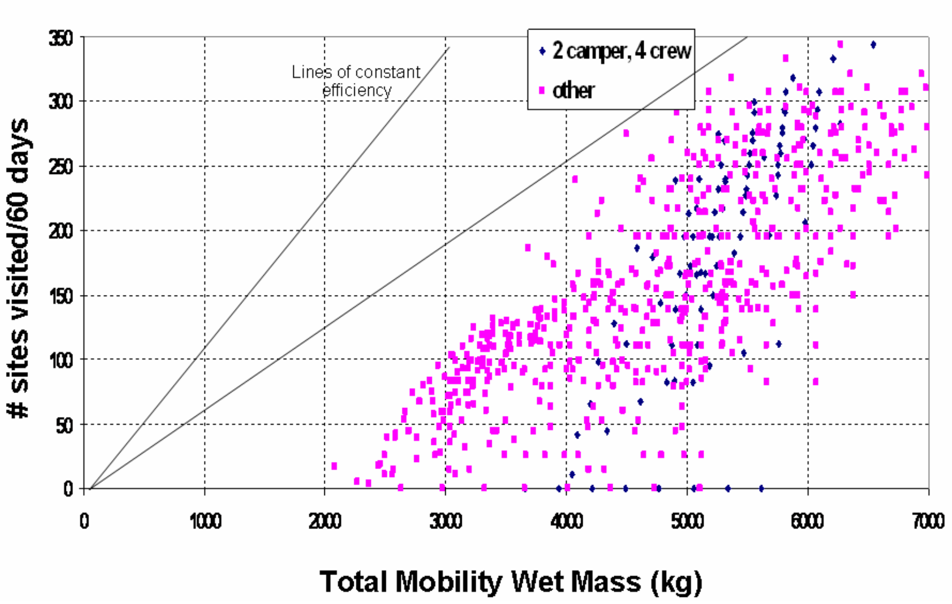


Figure 11: Lunar DRM-2 Tradespace

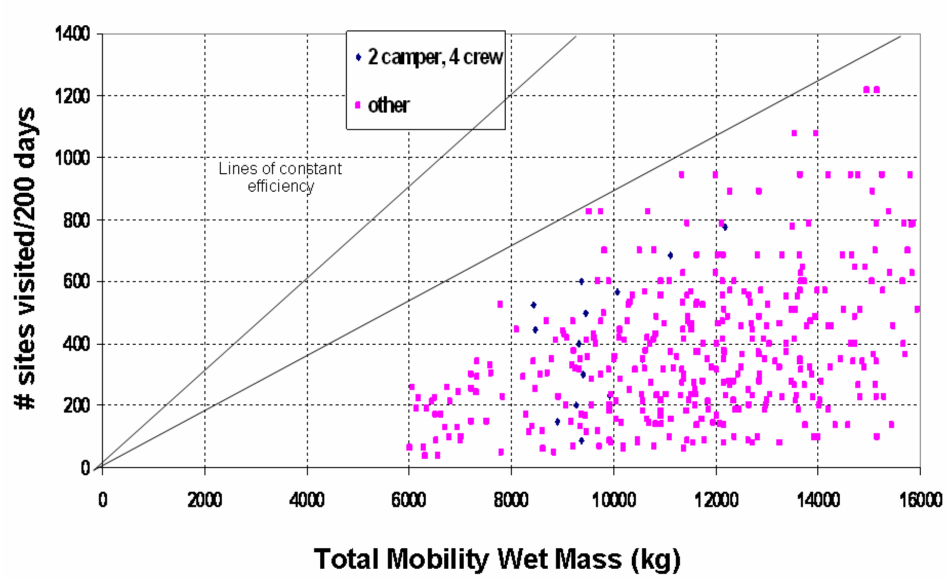


Figure 12: Mars DRM-2 Tradespace

These graphs suggest that the camper architecture is superior to that of the pressurized rover. Given that the designs are relatively similar, the most logical reason for this difference is that there is no repetition of the cockpit mass and steering mass in the camper system, like there is in the pressurized rover system. This reduction carries throughout the rest of the design, shrinking the chassis and the power system, to make the design more efficient.

Once again, the general trend was towards having the fewest number of vehicles. In other words, it is cheaper from a mass perspective to put extra crew in one vehicle, as opposed to creating new vehicles for the crew. However, there was some concern about having only 1 pressurized element. In the case that that vehicle was no longer functioning, there would be no ability to conduct long-distance exploration. Given the harsh environments of both the Moon and Mars, it was deemed reasonable to set a minimum of 2 pressurized elements. There is indeed a mass penalty to be paid for this decision, but the cost is worth the redundancy the extra pressurized element affords.

Extensibility played a role in the decision making process. Creating 2 campers with 3 crew each may make sense on Mars, but not on the Moon with only 4 crew. Therefore, the decision was made to use 2 campers with 2 crew each as baseline design. This architecture provided the best exploration efficiency, redundancy, and extensibility. However, given the many assumptions that must be entered in the model, the decision was made to create a “delta” design to be compared to the baseline. This “delta” design was designated to be 2 pressurized rovers with 2 crew each.

For the different environments (Moon, Mars, and Earth) the combined architectures are slightly different. On the Moon, there will be 3 UPVs accompanying the 2 pressurized elements. The reason for the extra UPV is to scout out ahead of the pressurized elements, helping to pick a reasonable path.

This architecture is a common-sense approach that should allow for more rapid and safer travel. Pascal Lee used this system successfully in the Haughton-Mars project for bringing the Humvee to Devon Island, and it is sensible to accept his advice in this area. The architectures on both Mars and Earth involve a fourth UPV, in order to provide mobility to the crew members left behind during a traverse. In this manner, the crew can continue with infrastructure build-up and/or re-supply as necessary. Additionally, this extra UPV provides a spare in case one vehicle breaks down. The overall baseline decisions are summarized below.

Table 9: Baseline Architecture Selection

Planet	DRM-1	DRM-2
Moon	2 upvs with 2 crew each	2 campers (2 crew each) with 3 upvs
Mars	2 upvs with 2 crew each	2 campers (2 crew each) with 4 upvs
Earth	2 upvs with 2 crew each	2 campers (2 crew each) with 4 upvs

Given the many assumptions inherent in this model, a sensitivity analysis was undertaken to verify the baseline choice.

3.4 Architecture Sensitivity Analysis

3.4.1 DRM-1

The first step was deciding which elements to vary. For DRM-1, two variables were chosen as having a potentially large impact on the design: speed and range. The same steps were undertaken as outlined in 3.3 and the appendix with the exceptions outlined in this table:

Table 10: DRM-1 Sensitivity Variables

Variable name	Range	Description
range	30 -70 km	Units of 5 km
speed	8-18 km/hr	Units of 2 km/hr
Power source	Fuel cells	No variation this time

The following figure shows the lunar DRM-1 speed graph, in which the range of values is from 8 to 18 km/hr by 2 km/hr increments.

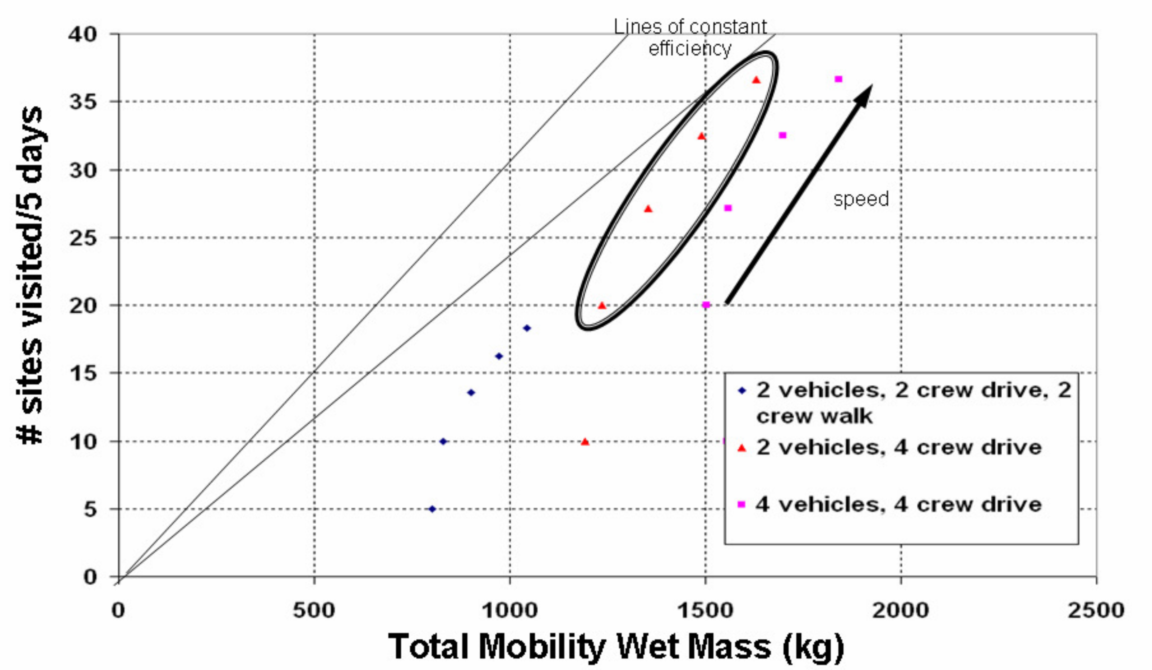


Figure 13: Lunar DRM-1 speed sensitivity

From the speed sensitivity analysis, it can be shown that after about 14 km/hr is reached, the efficiency does not change considerably. The arrow points in the direction of increasing speed. From this graph, the baseline architecture is clearly superior, having the highest efficiency.

For the range graph and analysis, see the Appendix. No graphs are presented for the Mars case, as there is expected to be no difference. Additionally, any trip to Mars is assumed to have a pressurized element due to the long stay times, so there is no analog to the lunar sortie mission where an analysis solely of a Mars DRM-1 option is necessary. It is clear that no change in the baseline architecture were needed for a lunar sortie mission.

3.4.2 DRM-2

For the DRM-2 architectures, 3 variables were chosen as relevant for conducting a sensitivity analysis, as seen in the following table. Otherwise, the same steps as outlined in the appendix were followed, with nominal values stated there.

Table 11: DRM-2 Sensitivity Variables

Variable name	Range	Description
range	240 – 360 km (Moon) 480 – 720 km (Mars)	Units of 30 km (Moon) Units of 60 km (Mars)
speed	8-16 km/hr	Units of 2 km/hr
duration	3-10 days	
Power source	Fuel cells	No variation this time

Only the sortie day graphs will be represented here, while the others will be placed in the appendix. The range graph is not a huge factor in mass (and due to the metric calculation method is not very informative) while the speed graph does not provide significantly different results from the sortie days analysis, which is seen below.

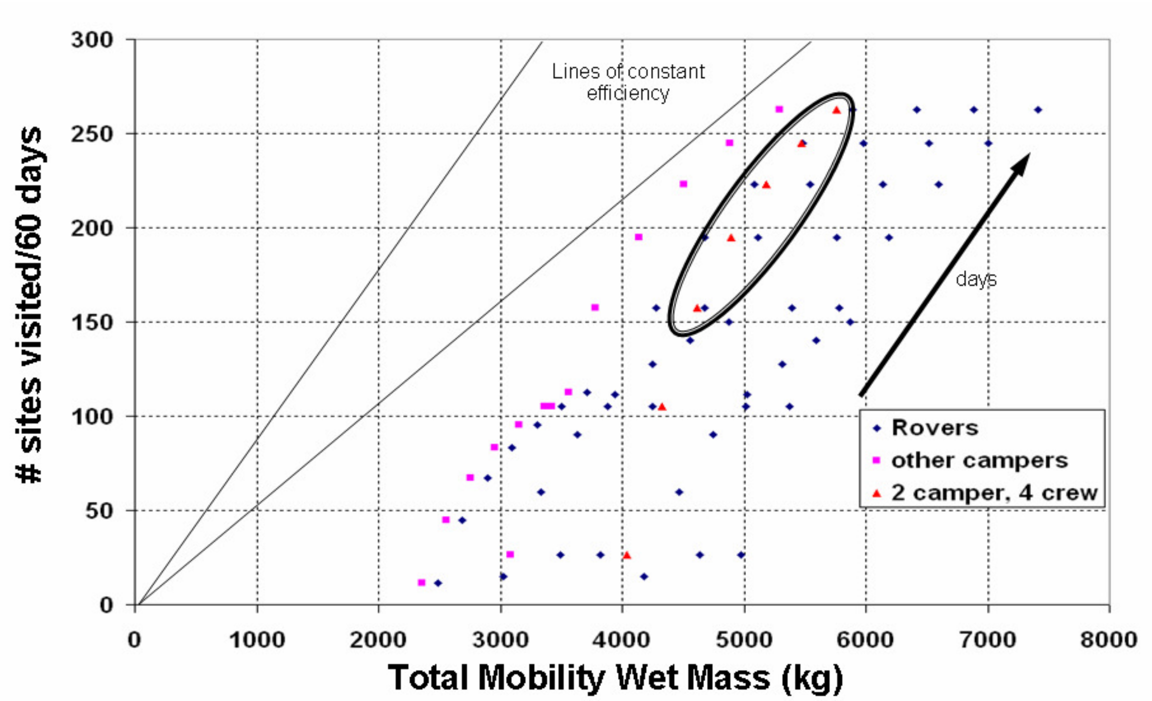


Figure 14: Lunar DRM-2 Sortie Days

In this graph, the 2 camper, 4 crew architecture is not along the Pareto front, but rather is dominated by two architectures. It is important to realize that these architectures are only single pressurized vehicles. To increase redundancy, the extra vehicle is worth the mass penalty that is incurred, as discussed previously. The arrow points in the direction of increasing sortie days.

Overall, the lunar sensitivity analysis shows no reason for a change in the baseline design.

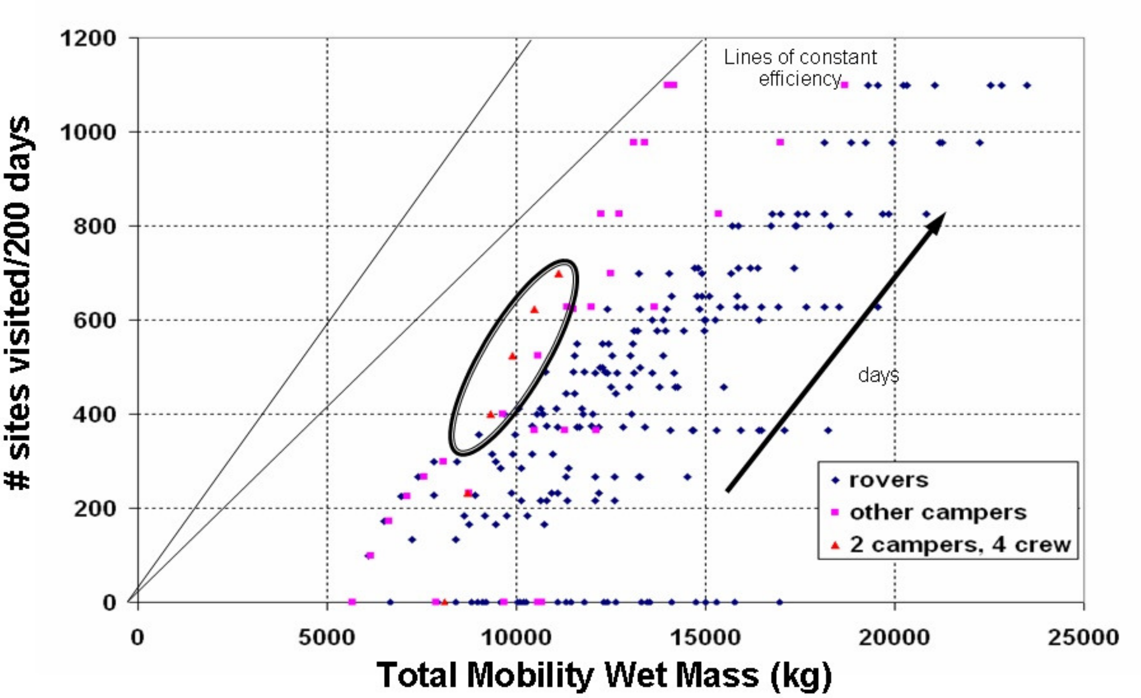


Figure 15: Mars DRM-2 Sortie Days

For the sortie days, once again the camper baseline architecture is along the Pareto front. However, it is not the most efficient design, but those designs all include a greater number of crew. In order to keep the design extensible, it makes sense to stay with the baseline. Additionally, given the overall mass constraints for the mobility system, and the high-level nature of this study, some margin between the 15,000 kg limit is a very good idea.

Once again, there is no need to change the architecture.

3.5 Communications and Navigation

The communications infrastructure is responsible for providing the transport of information from one asset to another in the planetary surface mobility system. This chapter overviews the proposed evolutionary architecture developed to meet the communications requirements and highlights the analysis performed to determine the feasibility of the architectural strategy.

3.5.1 Architecture and Deployment Strategy

The proposed architecture and communications deployment strategy is driven by the communications requirements (see the Communications & Navigation Appendix). The architecture and deployment study focused on the Moon as its case study.

It was found that the best communications architecture depended on two key factors:

- *Mission class*: Defined as the degree of Direct Earth coverage between lunar asset and at least one DSN station, assuming elevation angles of greater than 10 degrees, terrain grazing angles of greater than 5 degrees, and a lunar elevation angle of greater than 5 degrees. Figure 17 depicts the coverage map for the lunar surface. The lighter the color, the higher the duty cycle. The mission classes are defined as:

    - Continuous Direct Earth Coverage: 97% or better coverage over one year.
    - Cyclic Direct Earth Coverage, High Duty: Repeating, non-continuous access with greater than or equal to 50% duty over one year.
    - Cyclic Direct Earth Coverage, Low Duty: Repeating, non-continuous access with less than 50% duty over one year.
    - No Direct Earth Coverage: No access over one year.

- *"Hard" vs. "Soft" communication requirement*: Missions requiring continuous, real-time communications between the mobile asset and the Earth require a different minimal architecture than missions requiring only that the data be transported between the mobile asset and the Earth at some point.

The Ground Network architecture as shown in Figure 16(a) was found to be the best communications architecture for the following independent situations:

1. Continuous Direct Earth Coverage missions.
2. Nearside (anything other than No Direct Earth Coverage missions) with "Soft" communication requirement.
3. Border Far-side missions with nearside communications base.

The Full architecture in Figure 16(b) was found to be the best communications architecture for the following independent situations:

1. No Direct Earth Coverage missions.
2. Near-side (anything other than No Direct Earth Coverage missions) with "Hard" communication requirement.

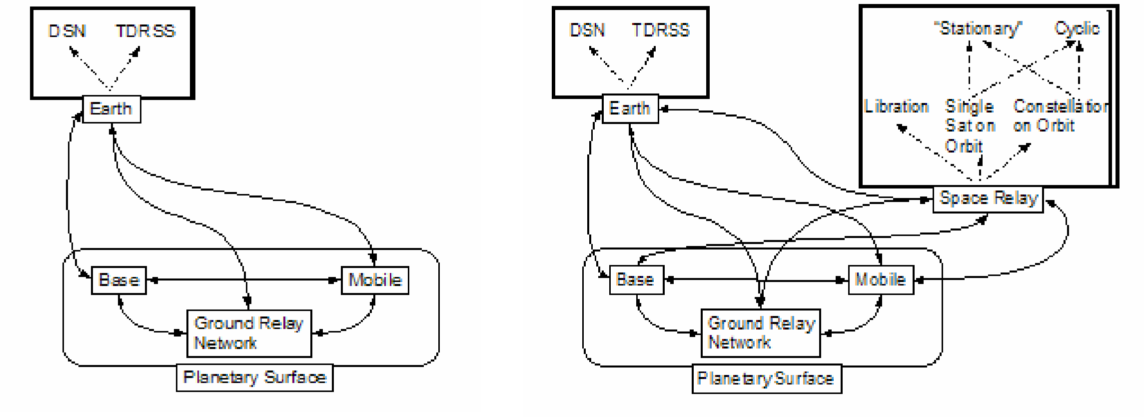


Figure 16: Architecture with (a) ground relays, (b) ground and space relays

Caveat: the communication requirements discussed in the Communications & Navigation Appendix imply that neither a ground network nor a space-based asset is required if the base and mobile asset remain in line-of-sight contact and the following independent conditions apply:

1. Continuous Direct Earth Coverage missions.
2. Nearside (anything but No Direct Earth Coverage missions) with “Soft” communication requirement.

Furthermore, neither a ground network nor a space-based asset is required for Continuous Direct Earth Coverage missions even if the base and mobile asset don't maintain line-of-sight contact so long as both assets can always communicate with Earth.

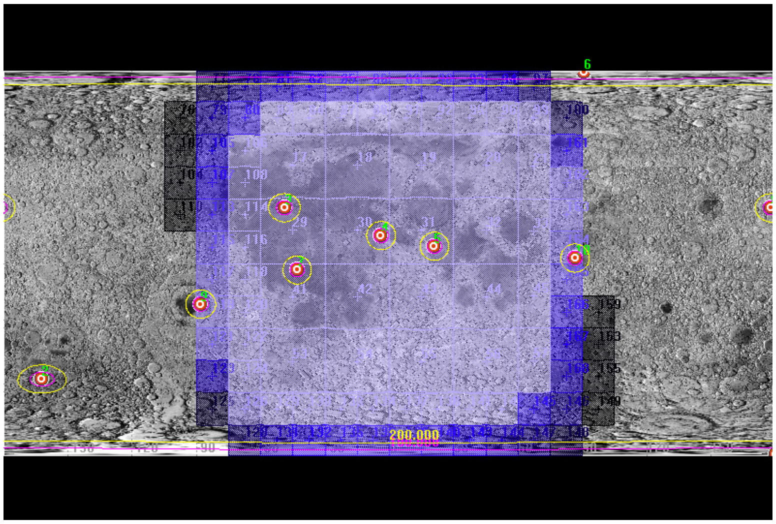


Figure 17: Coverage map with potential lunar exploration sites

Why not simply use direct-to-Earth for both base and mobile like Apollo? In some cases, this is indeed possible (as it was for Apollo). The elevation of the Earth above the horizon should be sufficient to mitigate terrain interference effects. The energy required to bridge the distance between the moon and Earth is significant and losing half the signal strength or more off the bat to terrain diffraction is a serious issue (which occurs if the top of the terrain is right at the line-of-sight path or higher).

In the cases described above, if the landing site is chosen in a Continuous Direct Earth Coverage region and is placed well, then the base should have guaranteed direct-to-Earth connectivity. However, this is not necessarily the case for the mobile asset as it may encounter terrain that blocks not only its direct connectivity to the base but also to Earth. Depending on the stringency of the communication requirements, this may or may not be a serious issue. Here, it is assumed that the system must have continuous communications between the base and mobile asset regardless of line-of-sight. Thus, in cases where terrain effects are not inconsequential and the elevation of the Earth above the horizon is low, a ground network will likely be required to maintain connectivity.

Even in instances where this is not the case, a ground network would provide communications redundancy and enable ground-based navigational capabilities. Also, placing the bulk of the communications equipment at the base rather than on the mobile allows the mobile asset to carry more scientific equipment and sample payload and enables higher-throughput communications back to Earth once the data arrives at the base. The precise benefits are not entirely clear, but there is sufficient motivation to consider architectures beyond Apollo-like and/or space-based constellations.

Since the best architecture depends not only on the location of the assets but the per-mission service requirements, the logical solution is to propose an evolving architecture.

An evolving architecture would have the following deployment strategy:

> "What is needed, where it is needed, as it is needed."

3.5.2 Hypothesis of Strategy

The feasibility of the communications architecture and deployment strategy strongly depends on whether a ground network can replace a space-based asset for planetary surface exploration. The hypothesis is that a ground network can provide comparable quality-of-service performance at a fraction of the price as compared to space-based assets. The remainder of this section will describe the first phase of hypothesis testing, where we investigate the number of relays, under a variety of conditions, which would be required to maintain connectivity to a lunar base.

Analysis Overview

Terrain data for the lunar surface were generated based on power spectral densities of several terrain types [Power]. These data sets represented terrain elevation for an area 2 km x 2 km, where each pixel represented an area of 2 m x 2 m, and the data represented the number of meters above or below nominal (represented by an elevation of "0"). There were four types of terrain analyzed (in order of roughness): smooth mare, hummocky upland, rough mare, and rough upland terrain.

Connectivity is determined by line-of-sight between a vehicle moving along the terrain and the relay network. Whenever a relay is deployed, the code calculates the *visibility map* of the relay; that is, the areas of the map that the relay can see. Whenever the vehicle moves outside this region, another relay is deployed. For multiple relays, the code keeps track of the *cumulative visibility map*, which is the area on the map that can be seen by any of the deployed relays. The line-of-sight tool *los2* in the MATLAB Mapping Toolbox is used to calculate these visibility maps.

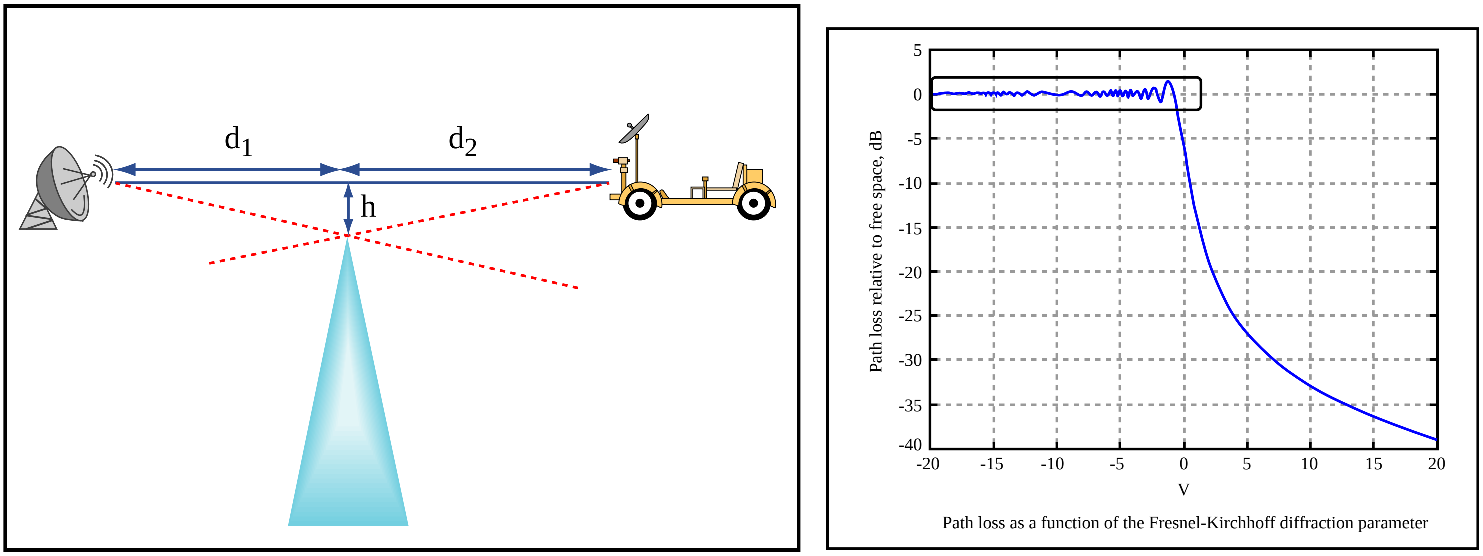
3.5.3 Effect of Line-of-Sight Assumption on Received Energy

The line-of-sight assumption in the MATLAB analysis results in a worst-case estimation of the number of relays to maintain network connectivity. The reason for this relates to the trade between communications range and received signal energy. MATLAB assigns line-of-sight connectivity if there are no obstacles in the straight-line path between the two locations as shown in Figure 18(a). If the top of an obstacle touches or is in the line-of-sight path, no connectivity exists. This is a restrictive assumption, since in reality signals can propagate over obstacles through diffraction.

According to the theory of single knife-edge diffraction, so long as an obstacle exists below the line-of-sight path, the received signal energy is approximately the same as the transmitted energy less the space loss due to distance (the distances considered here produce negligible space loss). If the top of the obstacle touches the line-of-sight path, then the received signal energy is half the transmitted energy and decreases steadily from there. This phenomenon can be seen in Figure 18(b), a plot of path loss relative to free space as a function of the Fresnel-Kirchhoff diffraction parameter [Parsons]. The boxed area is the signal strength variation as the top of the obstacle is brought closer and closer to the line-of-sight path but does not obstruct line-of-sight. In this case, the oscillations are small, and it is thus a reasonable approximation to assume the received energy is the same as the transmitted energy. When line-of-sight touches the top of a sharp obstacle, the path loss is 6 dB (half the signal strength). If line-of-sight is further obscured by the obstacle, the power loss increases [Parsons].

If the line-of-sight assumption is relaxed, however, the range of the transmitter will increase by enabling communications to areas on the far side of obstacles, but the received energy will be subject to knife-edge diffraction losses (Fresnel-Kirchhoff diffraction parameter greater than 0) as shown in Figure 18(b). This represents a new trade: rather than simply ensuring connectivity, the range of the system could be increased by taking advantage of terrain, but this would require increased signal power from the relays to compensate for the diffraction losses. This can be accomplished by adding an appropriate link margin.

For this analysis, however, we are restricting connectivity to be based on line-of-sight only. Future work in this area would incorporate diffraction effects.



Images by MIT OpenCourseWare.

Figure 18: (a) Single knife-edge diffraction.
(b) Path loss relative to free space due to diffraction effects.

3.5.3 Parameter Study

There are four parameters that are considered in the analysis to determine their effect on the number of relays required to maintain connectivity:

1. *Terrain type*: four terrain maps of varying roughness were used to measure the sensitivity of the required number of relays to terrain type.

2. *Deployment strategy*: when connectivity is lost and a relay must be deployed, the strategy determines where it is placed.
3. *Relay height*: the height of the relays impacts the areas with which they have line-of-sign connectivity.
4. *Start location*: on the same map, take a random sampling of start points in order to measure how the actual local terrain, not just the type, influences the results.

The metric used to compare simulations with different parameter values was the average distance between relays (meters / relay), which is a measure of how far one can travel before dropping another relay.

3.5.4 Deployment Strategies

There are two deployment strategies that were considered, which both rely on local terrain information to determine where to place the relays.

Straight-Line Deployment

In the straight-line deployment strategy, the vehicle travels in a straight line and continually checks if it has connectivity to a relay. If not, the vehicle drops a relay immediately behind it. This results in a string of relays in a line along the traverse path.

This is perhaps the simplest deployment method possible because it does not require the astronauts to alter the drive path to deploy relays. The strategy is operationally simple, as the vehicle could be equipped with an autonomous relay deployment system that acts independently of the astronauts. The method, however, does not take advantage of local terrain. Often it would be advantageous to place relays at nearby hilltops when another relay is required. Thus this strategy represents the upper bound on the number of relays needed since terrain is not used to boost the visibility of the relays.

Adaptive Deployment

The adaptive deployment scheme also has the vehicle driving in a straight line, but when connectivity is lost, a relay is placed at the highest elevation point within a specified radius from the vehicle. This represents our first attempt at introducing the ability to use the local terrain to our advantage. By placing relays at higher locations, the number of relays would conceivably be decreased since each relay can see larger areas of the terrain.

Alternate Strategies

There are many other approaches that were not considered in this analysis due to time limitations, but they fall into two major types. First, the assumption that the vehicle travels in a straight line could be relaxed, so that the vehicle itself travels to high points on the terrain to better utilize local elevation to boost range. Second, the above methods rely on local terrain information that becomes available only when the vehicle is in the immediate area. If terrain elevation data were known in advance, the relay locations could be optimized prior to the traverse. Therefore, our analysis represents the upper bound on the number of relays required, as there are much more intelligent ways of placing relays along the terrain.

Algorithm Details

The program simulates a vehicle moving east along the terrain, which is a section of the large map data that is 300 m long and 40 m wide. The vehicle starts by deploying a communications relay and starts driving in a straight line due east. At each map data point (2 m resolution), the vehicle checks if it has line-of-sight with the relay and continues to move while it does. When connectivity is lost, the vehicle deploys a relay based on the selected deployment scheme. As the vehicle continues to traverse the map, it checks every 2 m whether it has connectivity to *any* of the previously deployed relays, and continues until it reaches the end of the map.

The algorithm outputs the locations of the relays as placed by the vehicle on the surface. Figure 19 and Figure 20 illustrate the relay locations from one run on Hummocky Upland terrain with a relay height of 1 m and the straight-line deployment scheme. The colour scale indicates the elevation from nominal (+6m to –6m).

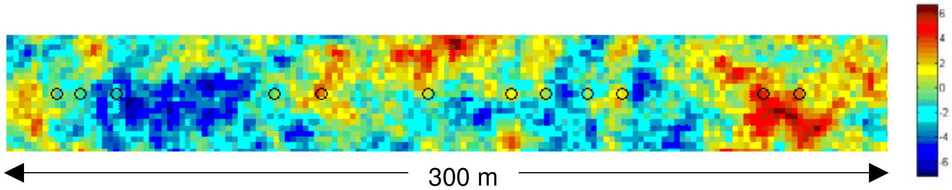


Figure 19: Locations of relays on the terrain from one sample run.

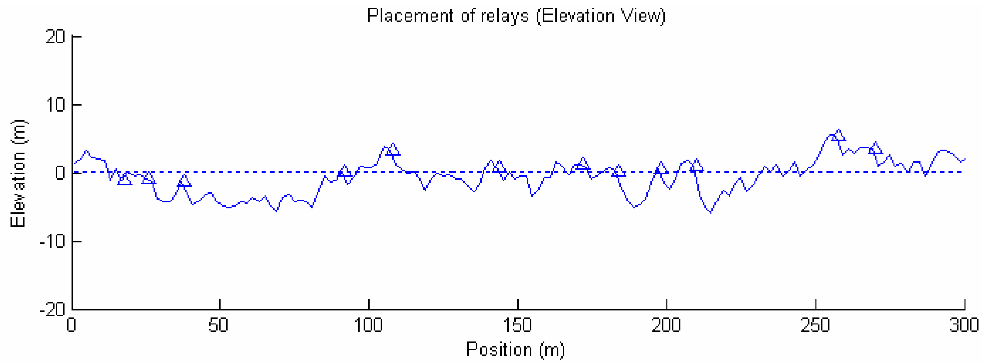


Figure 20: Location of relays, 2D elevation view.

In this particular run, a total of 12 relays were required to maintain connectivity throughout the traverse. The total distance between the first and last relays was 270 m, which gives a average distance / relay value of 22.5 m. This run suggests that approximately 44 relays with the properties listed above would be required for a 1 km traverse.

The algorithm also checks the connectivity at each point on the map after all the relays are deployed, which is a measure of the overlap and robustness of the network. The connectivity maps are shown in Figure 21.

The top image in Figure 21 shows the number of connections at each 2 m x 2 m pixel, which ranges from 0 (no connections) to 10. The bottom image shows in blue areas that have no connectivity. With some exceptions at the edges of the map, there are very few blind spots with no connection to any relay, and the sizes of these blind spots are on the order of only several meters.

3.5.5 Parameter Study Results

Four parameter studies were conducted to determine the effect of each parameter as discussed above.

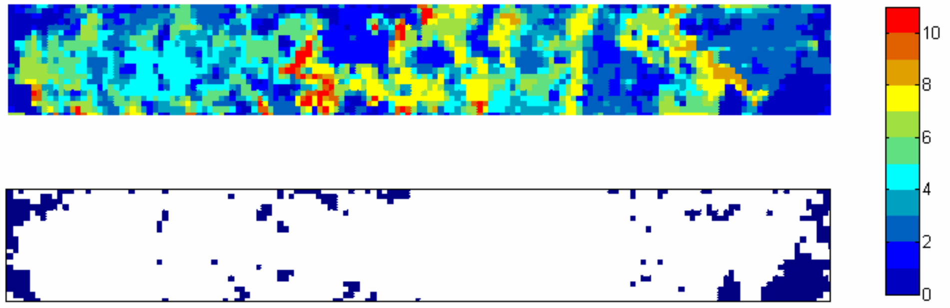


Figure 21: Connectivity maps of the sample run.

<u>Study 1: Map Location</u>

We ran the analysis with ten different start locations on the Hummocky Upland terrain map with one-meter relays, using the straight-line deployment strategy. The results show that on the same terrain type, the number of relays required has a large variance, which indicates the relay requirements are highly dependent not only on terrain type, but local elevation properties.

<u>Study 2: Terrain Types</u>

Using one-meter relays and the straight-line deployment strategy, we ran the analysis on the four different terrain types. The average distance between relays ranged from 11.4 m in the roughest terrain (Rough Upland), to 19.1 m in the smoothest terrain (Smooth Mare) as shown in Figure 22. The circles are the averages and the error bars show the minimum and maximum values for each terrain type. Thus the number of relays is highly dependent on terrain type, and even benign terrain will require a significant amount of relays.

<u>Study 3: Deployment Strategies</u>

With one-meter relays on Hummocky Upland terrain, we ran the analysis with both the straight-line and adaptive deployment strategies. Surprisingly, the straight-line strategy gave better results (average of 13.9 m/relay) than adaptive deployment (average of 11.4 m/relay). We believe this was due to problems with coding the adaptive algorithm, since there is no reason why placing relays at local high points would be worse than simple straight-line deployment.

The reason for the poor performance of the straight-line deployment is due to the fact that if a relay is dropped in any kind of depression, the vehicle will not travel far before it loses connection. This relay clustering effect can be seen several times in the relay location map in Figure 19.

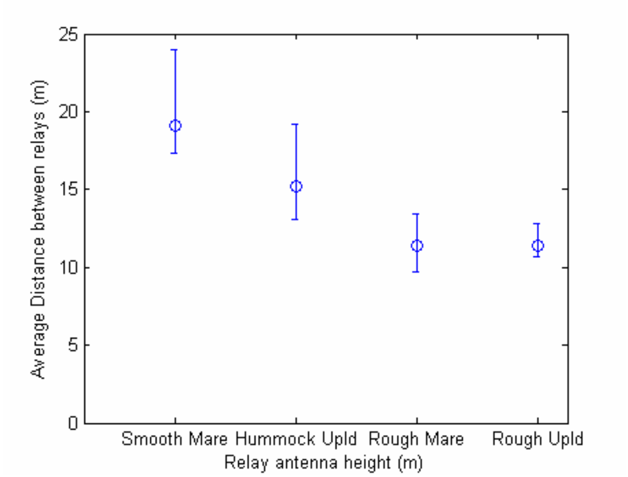


Figure 22: Average distance between relays for four terrain types

Study 4: Relay Antenna Heights

The code was then run for a range of relay antenna heights on the Hummocky Upland terrain data set. The results are shown in Figure 23, and suggest that the distance between relays scales linearly with relay height. In particular, the variance in the distance / relay metric increases dramatically for relay heights above 0.5 m.

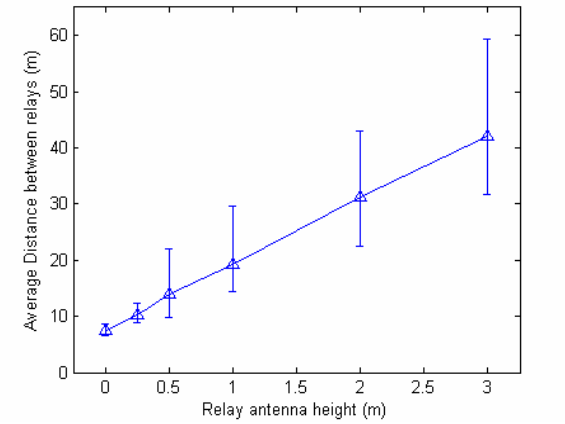


Figure 23: Average distance between relays as a function of relay height.

3.5.6 Analysis Summary

The communication over-the-horizon ground network evolution concept does not appear to be infeasible. The analysis represents a worst-case bound on the numbers and the parameter study shows that there are large variations in the number of relays required for relatively small changes in the parameters. The results strongly imply that better performance can be found if the design and deployment are intelligently constructed. If it had been found that there were very small variations in the number of relays, then the concept would likely be infeasible: the concept performs badly no matter what.

Conclusion: the ground network concept does not appear to be infeasible. More work will need to be done to determine under what conditions it is feasible.

[Parsons] Parsons, J.D. Mobile Radio Propagation Channel, 2nd Edition, John Wiley and Sons, LTD., NY, 2000.

3.6 Final Architecture Selection

No change was made after the sensitivity analysis. The final choices were as follows:

Table 12: Baseline Architecture Selection

Planet	DRM-1	DRM-2
Moon	2 upvs with 2 crew each	2 campers (2 crew each) with 3 upvs
Mars	2 upvs with 2 crew each	2 campers (2 crew each) with 4 upvs
Earth	2 upvs with 2 crew each	2 campers (2 crew each) with 4 upvs

A graphical representation of the DRM-2 architectures is seen in Figure 24 below for further clarity.

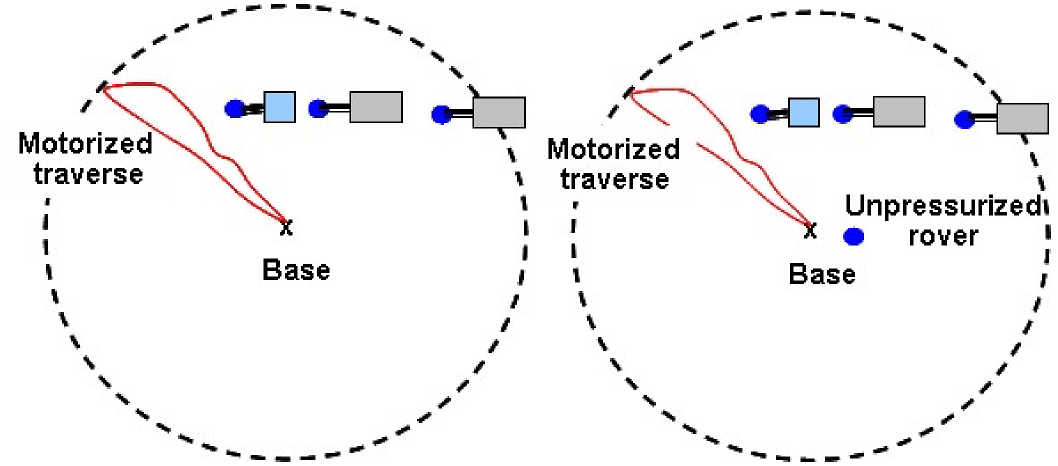


Figure 24: DRM-2 final architectures

4. Mobility System Design

4.1 Approach

The objective of the vehicle design study was to define concepts for the each of the two vehicles (camper and UPV) in each of the three environments of interest (Moon, Mars, and Earth). Rather than separately designing six vehicles, the focus was placed on the lunar camper and lunar UPV. A commonality analysis was then done in which the penalties and benefits of adapting the lunar vehicle designs to different environments were assessed. From this analysis an estimate of the relative mass of the Earth and Mars vehicles was made.

The vehicle design was done with the Terrain Vehicle Model (TVM), which is Matlab code created by the 16.89 students. Each subsystem was coded into a Matlab module, and then run iteratively until the vehicle properties converged to a design. The resultant lunar vehicle specifications were feed into MUSE. MUSE then provided a dynamic analysis of the vehicles' capabilities. Based on feedback from MUSE, the inputs to the TVM were varied depending on if the capabilities of the vehicle turned out to be over designed. After iterations between MUSE and TVM, the Planetary Surface Vehicle (PSV) model was used to perform the commonality analysis across the Earth and Mars environments. Figure 25 shows a flow chart of the vehicle design process.

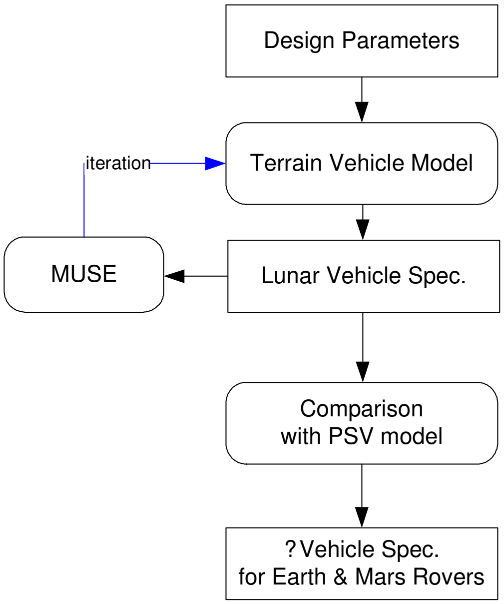


Figure 25: Block diagram of the vehicle design process

4.2 Assumptions

A set of top level assumptions were made in the interest of reducing the number of design variables and simplifying the vehicle model. Additional assumptions were made on the subsystem level and documented in their respective sections of this document. Both the camper and UPV are nominally designed to carry 2 crew members. Both vehicles also have 4 wheels and an Aluminum structure and chassis. The camper ECLS subsystem is assumed to be able to regenerate water. To estimate the quantity of consumables needed, it is assumed that the camper will carry out 125 excursions, each of which has a 7 day duration. It is assumed that 4 of the 7 camper excursion days are spent driving, while the other 3 are spent performing DRM-1 operations away from the camper. For the purpose of sizing the power subsystem, it is assumed that the vehicles drive up to 12 hours per day. Finally, the camper is capable of driving itself, but not steering. The UPV must be able to provide steering to the camper, but not tow its weight.

4.3 Subsystem Interactions

The Terrain Vehicle Model (TVM) written by the 16.89 students consists of a master script that calls each subsystem's module in sequence. The order in which these modules are run as well as the flow of information between subsystems is shown graphically in Figure 26. The feedback loops in the sequence are handled by running the code several times until the vehicle specifications converge.

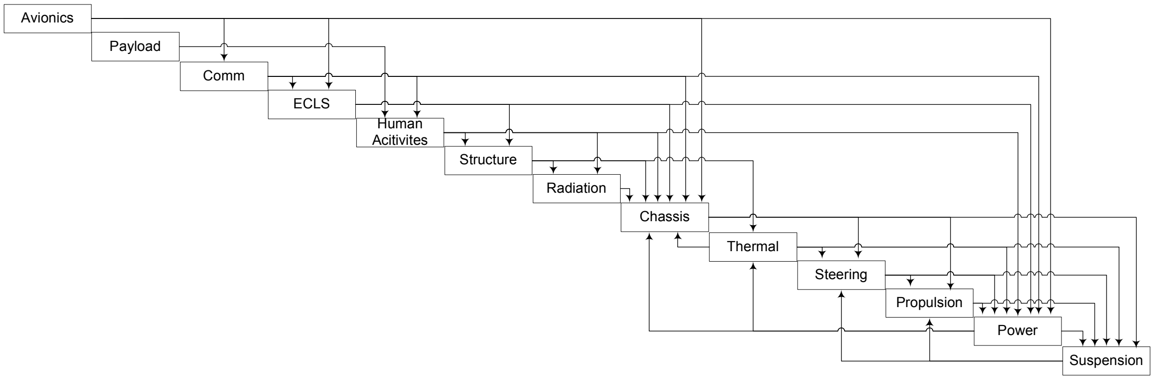


Figure 26: N^2 diagram of the Terrain Vehicle Model showing subsystem interactions

4.4 Subsystems

4.4.1 Thermal Subsystem

The inputs to the thermal subsystem are as follows:

Table 13 Thermal Inputs

Driving time heat load	Vehicle surface area
Science time heat load	Radiator choice

Using the environmental factors of solar flux, albedo reflection, and infrared (IR) emission in addition to the vehicle heat load determines the total heat that needs to be dissipated. Some of that heat is radiated through the thermal paint coatings over the camper. The remaining heat is radiated either through a vertical (bi-directional radiation) or horizontal (uni-directional radiation) radiator. Other components of the system include heat pumps, controls, fluids, plumbing, and multi-layer insulation (MLI). [Larson, 1999]

The code (see Appendix) is set up to run the exact same procedures for Mars. It is assumed that the internal fluid workings would not need to change, just perhaps the size of the radiators. This design should be acceptable anywhere on Mars, and at the poles on the Moon, at any time. For equatorial latitudes on the Moon, the environmental influences may require an additional thermal dissipation system, such as a reusable phase change system. [Eckart, 1999] For Earth, the radiators could be replaced by a convection system.

For the unpressurized elements, the design is similar. The same set of equations were used, but some louvers were added to protect sensitive equipment and a small phase change mass for heat dissipation in addition to the small radiators. These additions were based on the LRV, with information from a study on the Apollo 15 mission. [Costas, 1972]

The power is based on the amount of power required to punp the heat, and is seen in the vehicle design section for the camper (73 W or 87 W depending on situation). There is no power for the upv thermal system. The mass of each component of the thermal design for the Moon camper and upv is as follows:

Table 14 Camper Mass by Component

Component	**Camper**
Radiator (includes support)	139.9 kg
Mli	1.1047 kg
Pumps	37.426 kg
Plumbing	26.6023 kg
Controls	10.1975 kg
Fluids	10.7074 kg
Sum	**226 kg**

Table 15 UPV mass by component	
Component	**UPV**
Radiator (includes support)	3.98 kg
Mli	1.1047 kg
Small thermal sink	4 kg
Louver	3 kg
Sum	**12 kg**

4.4.2 Radiation Subsystem

The radiation system is very dependent on environmental factors, namely Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE)s. NASA has developed levels of acceptable radiation, outlined in the NASA-STD-3000. The critical number analyzed here is a maximum 50 REM exposure per year. Again, from NASA-STD-3000 [NASA-STD-3000], the average GCR at 1 AU was found to be 55 REM. The SPE was modeled after the six major events in 1989, which should be a conservative estimate. From the work of Wilson, et al. [Wilson 1997] a figure was found that identified various materials' ability to stop GCR. The Lunar Base Handbook had a figure giving similar data for the 1989 SPEs. [Eckart, 1999]

In addition to the radiation shielding, the material already in the camper can help stop radiation. It was assumed that the airlock itself provided 4 g/cm^2 in material. The entire vehicle structure, thermal components, etc., were assumed to stop an additional 5% of the SPE, a conservative estimate. Being low hydrogen materials, they would not stop any GCR, but rather cause cascading. The GCR total (55 REM) was divided by 1.75 to account for this occurrence, instead of by 2, since the Moon (or Mars) blocks half of the radiation value.

For Earth, no shielding is necessary, so this subsystem should be designed to be easily removable. The GCR on Mars is approximately 58 REM [Beaty 2005], but the SPE is reduced due to the increased distance from the sun. The values for Mars for the SPE were simply reduced by ¼ as a conservative estimate, since very little is known about how much the atmosphere and magnetic field protect the planet. A delta can be calculated here so any changes can be made for the new environment.

Table 16 Radiation Mass

Component	Camper	UPV
Polyethylene shielding	840 kg	0 kg

1. HSMAD
2. Lunar Handbook
3. LRV Bible
4. NASA-STD-3000. http://msis.jsc.nasa.gov/sections/section05.htm
5. Wilson, J.W., F. A. Cucinotta, M. H. Kim, and W. Schimmerling. "Optimized Shielding for Space Radiation Prtoection." 1st international workshop on Space Radiation Research and 11th Annual NASA Space Radiation Health Investigators' Workshop., 1997.
6. David W. Beaty (Mars Program Office-JPL/Caltech), et al. "An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars."

4.4.3 Environmental Control and Life Support Subsystem

The purpose of the ECLS subsystem is to provide a habitable environment for the crew during surface exploration. Major assumptions concerning the ECLSS included the following:

- Environmental control and life support is only required for the camper (see architecture selection above)
  - Design of space suits is beyond the system boundary
- The camper is continuously operated for excursions of 1-2 weeks duration
  - This is an important factor because it defines the frequency of re-supply and regeneration at an outpost / base for the camper
- Over the lifetime of the camper, on the order of 100 such excursions can occur
  - This is an important factor for determining the overall consumables required. Different technologies and regeneration strategies will be favored for different # of excursions.

The specific functions of the ECLS subsystem in our design are:

- To provide atmosphere management by:
  - Storing oxygen and nitrogen
  - Feeding oxygen and nitrogen to the cabin atmosphere
  - Removing moisture from the cabin atmosphere
  - Remove carbon dioxide from the cabin atmosphere
  - Remove trace gases from the cabin atmosphere
- To provide food / nutrition to the crew
- To provide water management by
  - Storing water
  - Providing drinking water to the crew
  - Providing hygiene water to the crew

Waste management functions, fire suppression, and crew accommodations and gear (such as a galley, hygiene, and medical facilities) are covered in the human activities subsystem. Temperature control of the cabin atmosphere is covered in the thermal control subsystem.

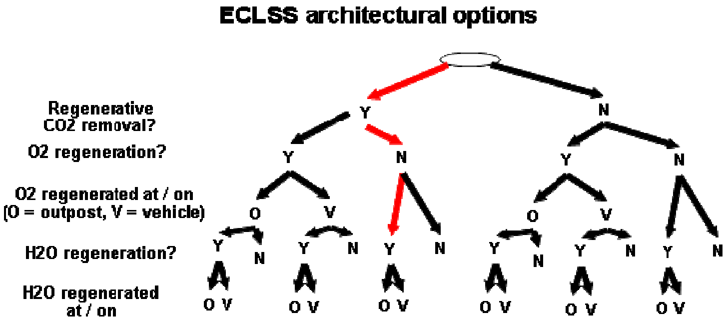


Figure 27: Overview of major ECLSS architecture options in the form of a trade tree

Figure 27 shows a trade tree for the ECLS system. Major architectural choices include:

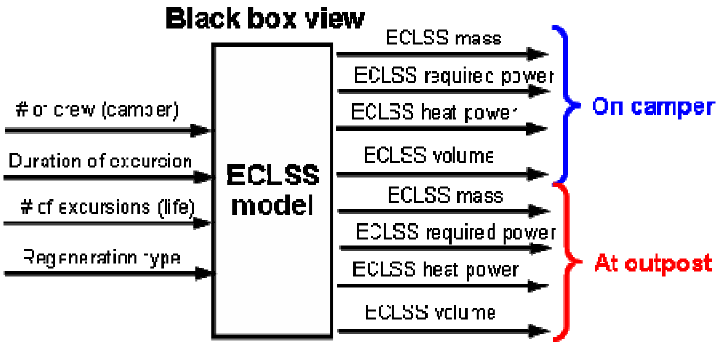
- The carbon dioxide removal mode: regenerative using SAWD / molecular sieves or expendable using LiOH

- Oxygen regeneration: no regeneration or regeneration using waste water of waste CO2, and whether the regeneration is carried out on the camper itself or after return to the outpost (i.e. the waste products are stored on-board the vehicle and then regenerated at the base)
- Waste water regeneration: whether water is regenerated using multi-filtration or not, and where the regeneration takes place

The red arrows in Figure 27 indicate the results of early subsystem-level trades carried out during the design phase:

- Regenerative CO2 removal is absolutely necessary because the LiOH ass and volume requirements for expendable CO2 removal are prohibitive. A molecular sieve system was preferred over SAWD, because the latter also removes and subsequently rejects water overboard which would then no longer be available for regeneration. For Mars, the molecular sieve can not be simply connected to the outside for evacuation of CO2 because the CO2 partial pressure of the Martian atmosphere is too high. In this case, a vacuum pump and a storage tank are required for CO2 removal from the sieves. The waste CO2 can then be pumped into a high-pressure tank and released to the Martian atmosphere from there.
- O2 regeneration was considered but rejected because of the limited impact on re-supply and the significant power requirements (several hundred W for 2 crew) which would have to be satisfied continuously. Should that power be available, it would likely have more impact when invested into O2 ISCP at the outpost than continuously on the camper.
- Water regeneration using multi-filtration is comparatively cheap in terms of mass and power (about 80 W for 2 crew) and has a significant impact on the re-supply mass (more than 50 % of the daily consumables required are water). It was therefore decided to baseline water regeneration.

Figure 28 shows a black box view of a parametric ECLSS model that was created in the form of a Matlab script. The model was integrated with other subsystem codes and used for vehicle level design (see below).



Mathematical model is based on equipment parameters provided by HSMAD [1]

Figure 28: Black box view of the Matlab ECLSS model

The mode takes the # of crew, duration of the excursion before return to the outpost, # of excursions over the lifetime of the system / exploration program, and the water regeneration type (actually location: outpost or vehicle), and provides cumulative ECLSS mass, power, heat power to reject, and volume on the vehicle and at the outpost. The outpost outputs were intended to enable a holistic comparison of vehicle designs taking into account recharging and re-stocking of the mobility elements at the outpost.

Using the above model, it was determined that water regeneration on the camper was preferable because of the low power, mass, and volume requirements. Figure 29 provides an overview of the baseline ECLSS design and some ECLSS components in use on the shuttle and the ISS; these components could potentially serve as legacy elements for use on the camper.

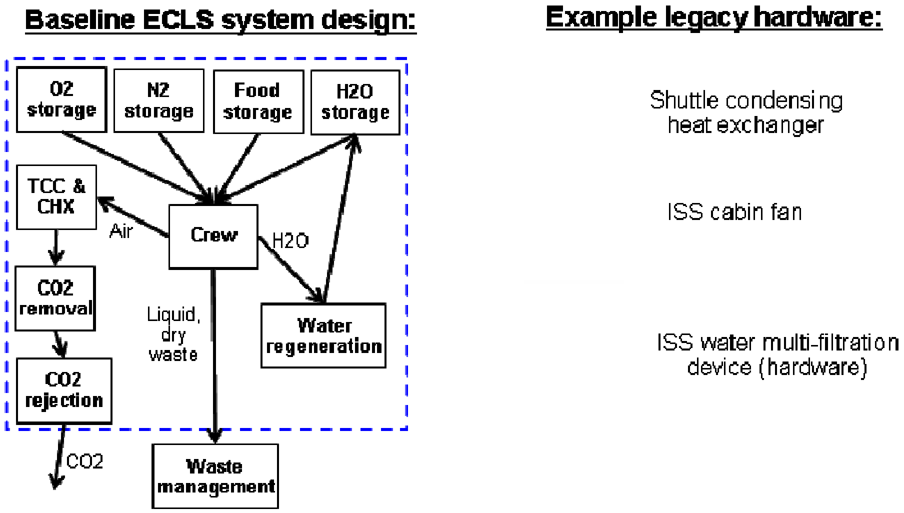
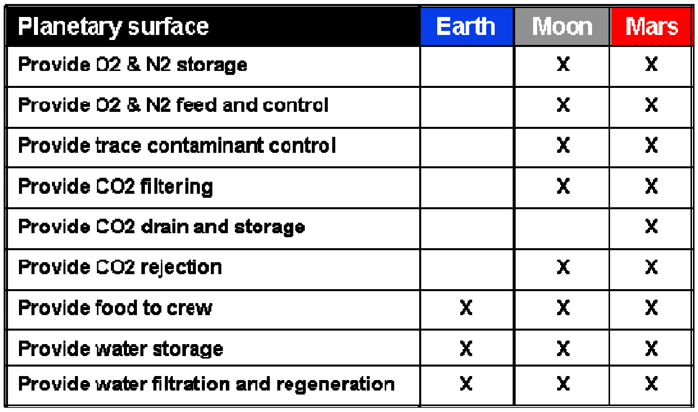


Figure 29: Baseline ECLSS architecture / design and existing components from ISS / shuttle that could in principle be used as legacy elements

The baseline ECLSS design provides the crew with oxygen from high-pressure tanks. The normal atmospheric pressure is set at 10.2 psi to limit pre-breathing time for EVA to a maximum of one hour. The differential between the oxygen partial pressure and 10.2 psi is provided using nitrogen stored in high-pressure gas tanks. CO2 is removed from the atmosphere using molecular sieves like those on Skylab. Water is removed from the atmosphere using a condensing heat exchanger; the condensate water is stored for regeneration. 80 % of the waste water on-board the camper is regenerated, the remaining 20 % are expendable. This means that most of the drinking water is non-recycled.

The design described above was a lunar camper ECLSS point design. Figure 30 provides an overview of ECLSS functionality required for the other two use cases on the Earth, and on Mars. For use on Earth, the camper need not provide atmosphere management, because equalization with the outside atmosphere will take care of CO2 partial pressure and provision of oxygen; if the camper crew compartment is hermetically sealed on Earth, then equalization valves would have to be included. For use on Earth in a remote environment, the camper still needs to provide food and water for the crew, and potentially water regeneration.

For use on Mars, the camper needs to provide the same functions as for the lunar use case. As mentioned above, CO2 rejection to the outside is more difficult on Mars because of the CO2 atmosphere and requires additional pumps and storage devices. These have been taken into account for sizing the Mars ECLSS.



Planetary surface	Earth	Moon	Mars
Provide O2 & N2 storage		X	X
Provide O2 & N2 feed and control		X	X
Provide trace contaminant control		X	X
Provide CO2 filtering		X	X
Provide CO2 drain and storage			X
Provide CO2 rejection		X	X
Provide food to crew	X	X	X
Provide water storage	X	X	X
Provide water filtration and regeneration	X	X	X

Figure 30: Functional extensibility matrix for camper ECLSS with Earth, Moon, and Mars use cases

Based on Figure 30 and the analysis presented above, it appears that ECLSS commonality / platforming between Earth / Moon / Mars campers is comparatively straightforward if the following two requirements are considered during design:

- Scarring of the lunar CO2 removal system for addition of a vacuum pump and CO2 storage and rejection system for use on Mars
- Modularization of the atmosphere management functionality / equipment so that it can be easily removed for use of the camper ECLSS on Earth.

Future work in camper ECLSS could include:

- Analysis of the impact of ISCP at a lunar and Mars outpost
- Integration / interaction / commonality of the camper ECLSS with the EVA suit ECLSS; analysis of the potential for mass and risk reduction

4.4.4 Power Subsystem

The power subsystem function was to meet the power needs of each of the subsystems. From the results of the architecture study, primary fuel cells were baselined as the energy source. The power subsystem code worked by reading in the power needs of each subsystem in different power modes, computing the energy required, and sizing the energy storage. The power distribution and control mass was sized using the peak power from the driving mode.

For the case of the long traverse, the pressurized elements held the fuel cells for the unpressurized elements. By providing the majority of the power, the unpressurized elements could be less massive for more efficient science exploration.

The major trades for the subsystem were the methods of power generation and energy storage. The candidates for energy storage were batteries and fuel cells, and from the architectural analysis fuel cells were chosen. The possible methods of power generation were solar arrays and radioisotope thermal generators, and the functionality to handle these were in the power subsystem model. However, due to time constraints and complexity, this trade study was not fully carried out, and fuel cells as a primary source were used.

The inputs to the power subsystem were the power requirements for the driving mode, science mode, and standing mode. Also the time spent driving in a day, and the numbers of science days, driving days, and total days were inputs. This would allow for calculation of the energy required. Finally the number and energy requirements of the unpressurized vehicles were inputs, and would come from running the vehicle model for the unpressurized case.

The outputs of the power subsystem were the mass and volume of the power equipment. The mass distribution of the subsystem between the pressurized and unpressurized elements was also an output. The thermal power to be dissipated was an output of the power subsystem, and was a function of the power needs. The water produced by the fuel cells was an output so that the water could be used by the ECLS or radiation shielding subsystems. Finally, the capabilities of the power subsystem were outputs to be used by MUSE.

4.4.5 Human Activities Subsystem

Description

Purpose

The Human Activities Module calculates the volume, mass, and power necessary to support normal human activities in the course of an excursion. It further determines the inner length and radius of the cylindrical habitat. The concepts considered for this model are distinct from general life-support systems. Table 17 lists the activities and items covered by this module.

ID	Human Activity	Volume (l, w, h)	Mass	Equipment	Power
	General				
1	**Control**	1m x 1m x 2.15m	100 kg	Cmd, Cntrl, Comm, Steering, etc.	0.2 kW
2	**Living space**	5m^3/person	-	-	
3	**Fire suppression**	0.1 m^3	10 kg/extinguisher	Extinguishers	0.02 kW
4	**Interior lights**	0.01 m^3	5kg	-	0.1 kW
5	**Medical Emergency**	0.5 m^3	10kg	paramedic equipment & storage	
	Consumables				
6	**Food**	(1/500) m3/kg	2kg/day/person	food reconstitution & heating, food storage, waste containment	
7	**Water**	water mass/998 m^3	5kg/crew-day		
	Hygiene				1 kW-hr/crew-day

8	**Self**	1m x 1m x 2.15 m	50 kg	bathroom, sponges, drainage, waiste containment	
9	**Personal Gear**	0.05 m^3/crew-day	1 kg/day/person	fresh and soiled clothing storage	
	EVA				2 kW-hr/EVA
10	**Ingress/Egress**	2.5m^2 x 2.15m	30 kg/m2	air lock	
11	**Suits on-off**	-	120 kg/suit	suits	
12	**Oxygen**	0.01*gas mass m^3	0.63kg/crew-day		
13	**Water**	water mass/998 m^3	5 kg/person/EVA		
	Working				
14	**Maintenance**	0.5 m^3	10kg	tools storage	
15	**Work station**	1.5 m^3	100kg	computer	

Table 17: Human activities subsystem overview

Assumptions

We made several assumptions in designing the human activities module.

Kitchen

To save on weight and volume we assumed no kitchen in the camper. Instead the crew will eat MRE-style meals

Sleeping

Instead of designing fixed sleeping births, we assume the crew will sleep in hammocks hung across the width of the camper. These hammocks would be setup at night and stowed during the day.

Living Space

The living space is assumed rectangular except for the ceiling which is bounded by the curved inner roof of the camper shell. The minimum standing height in the center of the camper is 2.15 meters which is based on a maximum crew height of 74 inches plus a 10.6 inch allowance for extra height due to the EVA suits. Further, the floor width is fixed at three meters. See Figure 31.

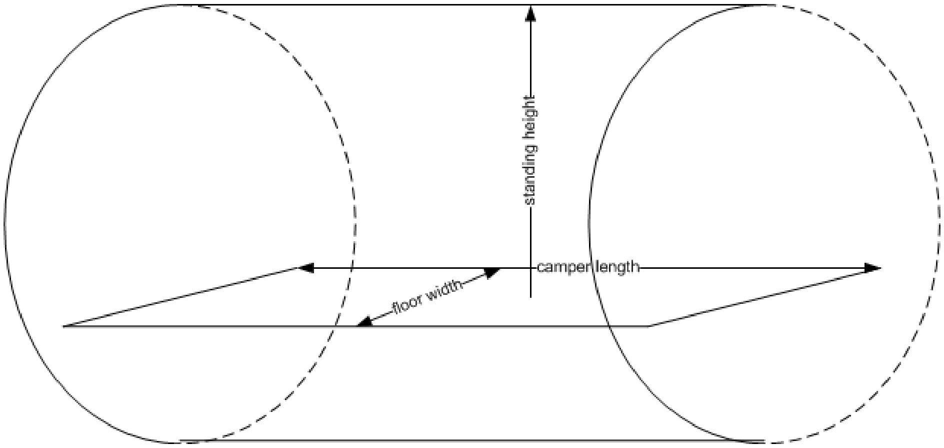


Figure 31: Crew compartment geometry

Space Division

The space inside the camper shell is split into living space and storage space. Since the camper is cylindrical and the living space is rectangular, all the space between the living space and the camper shell is considered storage space for things like water, food, supplies, etc.

Parameters

The inputs and outputs for the Human Activities module are summarized in Table 18 below. The science payload volume and mass are added to the other HA volumes and masses calculated within the module.

Inputs – Variables	
num_crew	Number of Crew
exc_days	Excursion Duration
sci_vol	Science Payload Volume
sci_mass	Science Payload Mass
num_eva_per_exc	Number of EVAs
Inputs – Parameters	
floor_width	Floor Width
airlock_floor_area	Airlock Floor Area
hmn_spc_h	Standing Height
Outputs	
vol_tot	Total Internal Volume
living_height	Standing Height
length	Internal Length of Cylinder
radius	Internal Radius of Cylinder
cntr_to_floor	Distance from cylinder center-point to floor
floorChord	Distance from one inner cylinder wall to the other along the plane of the floor
airlockSurfaceArea	Inner surface area of the airlock
drivingPower	Power consumed by HA during driving
peakPower	Power consumed by HA during peak periods
sciencePower	Power consumed by HA during EVAs
nightPower	Power consumed by HA during night
wtrConsump	Water consumed during excursion
heatGen	Heat generated by HA

totMass	Total mass required by HA

Table 18: Human activities module specifications

Function

Power, Mass, and Volume

Power, mass, and volume are calculated by integrating the amounts of each item needed for human activities for the number of crew specified over the period of the excursion and given the number of EVAs. These calculations are straight-forward and consistent. The volume calculation is split into living space volume and storage volume. Items that are stored, such as personal gear, water, etc. are added to storage volume; whereas structural items, living space, etc. are added to living space. These two volumes together set the lower bound on the cylinder's internal volume and separately set the lower bounds on the living space volume and storage space volume. These volumes are then used in the optimization described below to determine the radius and length of the cylinder.

Optimization

To determine the radius and length of the cylinder the HA module performs an optimization with the objective of minimizing the difference between the total volume as calculated by the objective function variables and the specified total volume determined by summing the above determined living space and storage volumes. Please reference Figure 32.

Minimize:

total volume difference (tvd)

Design Vector:

[d, d′, h, l]

S.T.:

standing height (sh) ≥ minimum standing height (msh)
storage volume (sv) ≥ summed required storage volume (srsv)
living volume (lv) ≥ summed required living volume (srlv)
floor chord (fc) ≥ specified floor width (sfw)

Where:

$$msh = 2.15m$$
$$sfw = 3m$$
$$sh = h + d + d'$$
$$r = d + h$$
$$h' = r - h + d'$$
$$lv = l * \left(\left(h' + 3\right) + \left(r^2 * \left(sfw / r - \sin\left(sfw / r\right)\right) / 2\right)\right)$$
$$sv = \pi * r^2 * l - lv$$
$$fc = 2 * \sqrt{\left(r^2 - d'^2\right)}$$
$$tvd = \left|sv - srsv\right| + \left|lv - srlv\right|$$

Two additional modules are used to perform the minimization: canSize and canSizeConstrFun. The canSize module contains the objective function and canSizeConstrFun contains the inequality constraints. The HA module uses the MATLAB *fmincon* function to perform the optimization passing in canSize and canSizeConstrFun.

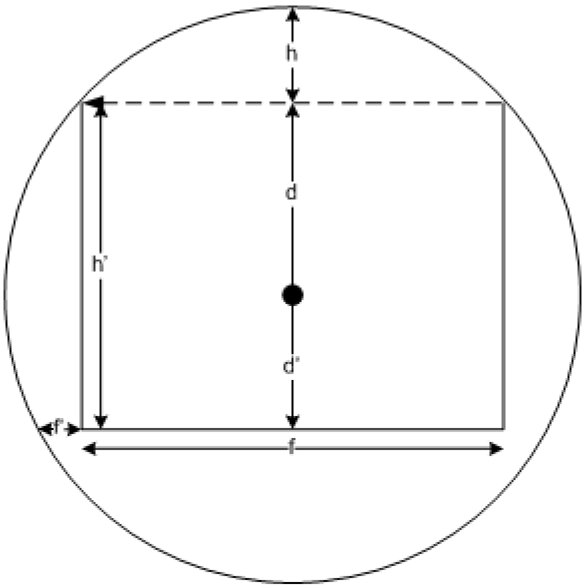


Figure 32: Crew compartment cross-section

References

[1] Wiley J. Larson and Linda K. Pranke. Human Spaceflight Mission Analysis and Design. McGraw-Hill Companies, 1999. Pages 447-476.

4.4.6 Steering Subsystem

Inputs:

Number of steered wheels [-]	Sprung mass [kg]
Wheel base [m]	Wheel track [m]

Outputs:

	UPV
Mass of steering [kg]	14.8
Turning radius [m]	4.76

The steering module is simple and assumes Ackerman steering for the vehicle. It models the mass of steering motor required for each steered wheel with additional linkages. The additional mass is estimated to be 4 kg based on data of electrically powered steering system in current vehicle. [1] It is also assumed that steer-by-wire system is on the vehicle.

The motor power is modeled as:

$P_m = 960/(1600 \times 0.8) m_s$

where P_m is motor power in Watts and m_s is sprung mass representing vehicle body mass in kg. The equation is based on an empirical data. [2, 3] The motor mass is then obtained from another empirical model based on masses of current motors.

The wheel turn angle is assumed to be 50°. Ackerman steering holds the following equation:

$$\cot\alpha = \frac{l_t}{l_b} + \cot\beta$$

$$\sin\alpha = \frac{l_b}{R_t}$$

where, α is the turning radius, β is the wheel turn angle, l_t is the wheel track, and l_b is the wheel base. [4] (Fitch, 1994)

Reference

1. http://www.freescale.com/webapp/sps/site/application.jsp?nodeId=02Wcbf07jS1504
2. International Standard ISO 2631-2, Evaluation of Human Exposure to Whole-Body Vibration-Part2:Human Exposure to Continuous and Shock Induced Vibrations in Buildings (1 to 80 Hz), International Standards Organization, 1989.
3. http://www.worldautosteel.org/ulsas/General/Background2.pdf
4. J.W. Fitch, Motor Truck Engineering Handbook, 4th Edition, 1994

4.4.7 Suspension Subsystem

Inputs:

Sprung mass [kg]	Unsprung mass [kg]
Tire stiffness [N/m]	Spectral power density of terrain

Outputs:

	Camper	UPV
Spring Stiffness of suspension [N/m]	74000	15000
Damping coefficient of suspension [Nm/s]	10000	1000
Mass of suspension [kg]	355.5	68.9

The suspension module takes a sprung mass, unsprung mass, and tire stiffness as inputs in order to specify the suspension characteristics, such as suspension spring stiffness, damping coefficient and mass of suspension. The sprung mass represents the vehicle body and the unsprung mass represents the wheels and associated components.

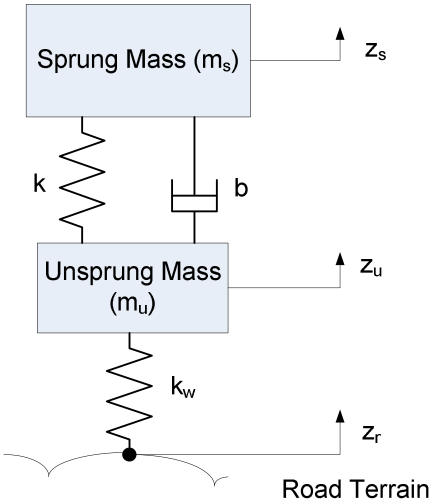


Figure 33 Quarter-car model

A simple two-degrees-of-freedom passive quarter-car model in Figure 33 is used for modeling suspension system. The equations of motion of the system can be obtained by applying Newton's law to the sprung and unsprung mass separately. [5] (Wong, 2001)

$$m_s\ddot{z}_s + b(\dot{z}_s - \dot{z}_u) + k(z_s - z_u) = 0$$

$$m_u\ddot{z}_u + b(\dot{z}_u - \dot{z}_s) + k_w(z_u - z_s) = z_r$$

where m_s is the sprung mass, m_u is the unsprung mass, b is the damping coefficient of the shock absorber, k is the stiffness of the suspension spring, and k_w is the equivalent spring stiffness of the tire. In addition, the natural frequency of the sprung mass is followed;

$$f_{n-s} = \frac{1}{2\pi}\sqrt{\frac{kk_w/(k+k_w)}{m_s}}$$

Now, both input due to when surface irregularities and output indicating vehicle vibrations of the sprung mass can be expressed in the transfer function H(f).

$$|H(f)| = \left|\sqrt{\frac{1+(2bf/f_{n-s})^2}{[1-(f/f_{n-s})^2]^2+[2bf/f_{n-s}]^2}}\right|$$ where f is the frequency of excitation.

The relationship between input and output is shown in the block diagram, Figure 34. and the surface irregularities expressed in terms of power spectral density function S_g(f) in Figure 35.

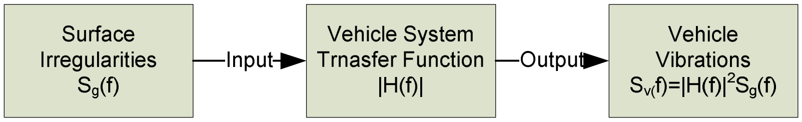


Figure 34: Input and output of a vehicle system

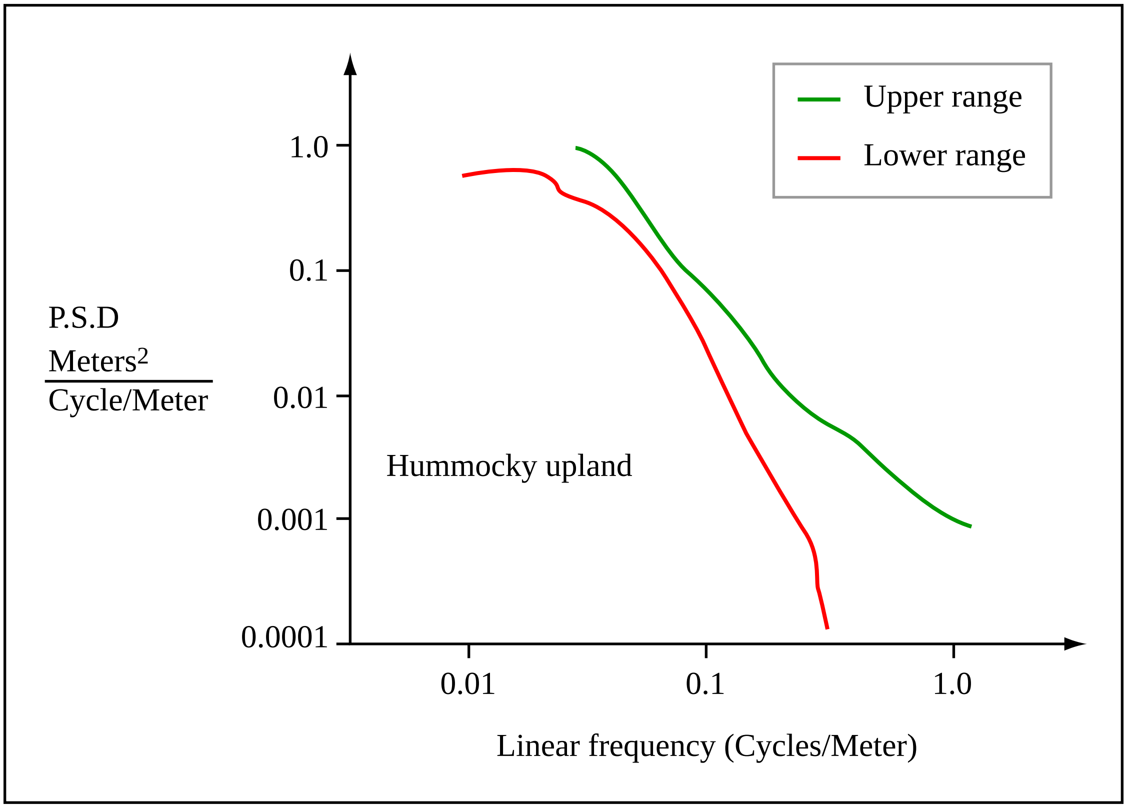


Image by MIT OpenCourseWare.

Figure 35: Power Spectral Density Function of the hummocky upland on the moon

After the spectral density function for acceleration of the vehicle, a ride comfort criterion is applied. The International Standard ISO 2631 suggested the boundaries for vertical vibration, and the transformation of the spectral density function into root mean square values of acceleration as a function of frequency is required. [2] (ISO, 1989) The root mean square value of acceleration at each center frequency f_c is given by

$$\text{RMS acceleration} = \left[\int_{0.89 f_c}^{1.12 f_c} S_v(f)\,df\right]^{1/2}$$

where S_v(f) is the spectral density function for the acceleration of the vehicle. After obtaining the root mean square value of the vehicle at a series of center frequencies, the vertical vibration of the vehicle can be evaluated against the criterion provided by ISO 2631.

Figure 36 and Figure 37 show the computed vertical acceleration of a camper over a hummocky upland on the moon evaluated against the ISO criterion.

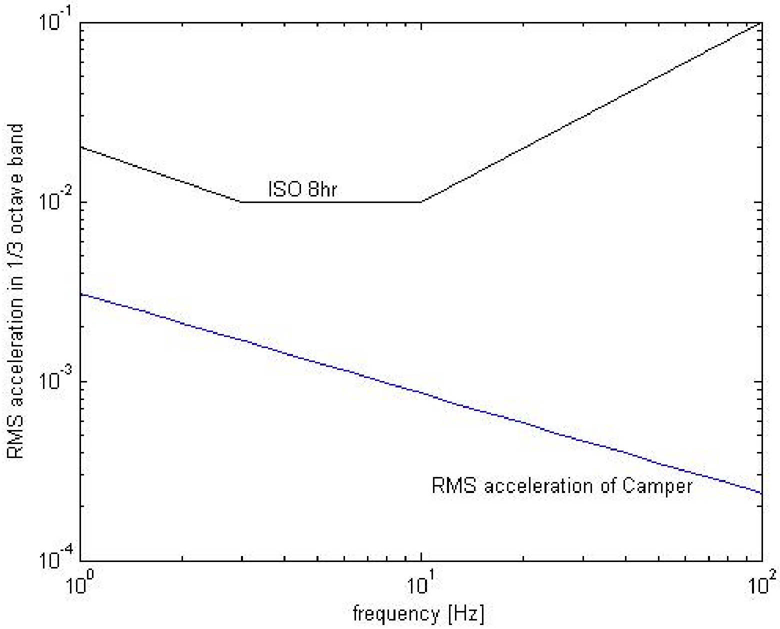


Figure 36: Computed vertical acceleration of a camper over a hummocky upland on the moon

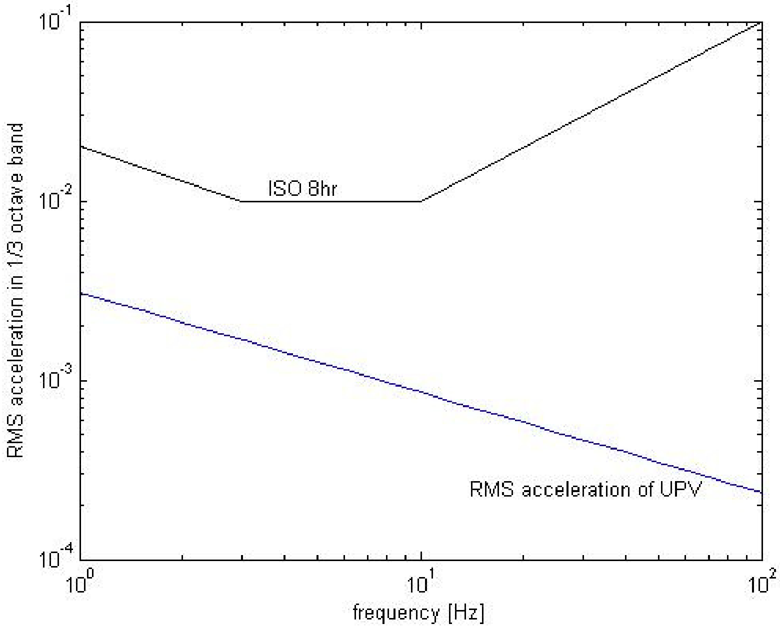


Figure 37: Computed vertical acceleration of an UPV over a hummocky upland on the moon

The mass of suspension system is modeled as a simple percentage of the vehicle body mass and assumed to be 10% of the sprung mass. The percentage, 10%, is obtained from an empirical data of commercial passenger vehicles. [3]

Reference

5. J.Y. Wong, Theory of Ground Vehicles, John Wiley & Sons, 2001
6. International Standard ISO 2631-2, Evaluation of Human Exposure to Whole-

Body Vibration-Part 2:Human Exposure to Continuous and Shock Induced Vibrations in Buildings (1 to 80 Hz), International Standards Organization, 1989.
7. http://www.worldautosteel.org/ulsas/General/Background2.pdf

4.4.8 Avionics

The avionics model for the TVM is of relatively low-fidelity. Table 19 shows the assumed parameters of the avionics subsystem. These numbers were estimated based on experience gained from the CER study as well as comparisons with existing avionics subsystems on space vehicles.

Table 19: Avionics subsystem parameters

	Camper	UPV
Mass	200 kg	20 kg
Volume	0.25 m^3	0.02 m^3
Power	300 W (driving) 400 W (science)	100 W

4.4.9 Propulsion

4.4.10 Chassis subsystem

There are two chassis subsystem in TVM; one for the camper and one for the unpressurized vehicle (UPV). The camper chassis is modeled after a ladder chassis while the UPV chassis has an additional railing to provide extra support. The primary requirement of this subsystem is that it must to able to support the vehicle during normal operations, contingencies and in an accident. It must also provide enough volume to house the different subsystems along with the crew compartment in the case of the camper. In addition, the chassis acts as an integrating station for all the various subsystems.

Assumptions

This model sizes the chassis based on the dimensions of the crew station and the total mass it will have to carry. The model for the camper assumes a ladder chassis design. Similarly the model for the UPV assumes a ladder chassis with the addition of a center railing to supply additional support. The loading is also assumed to be vertically distributed uniformly along the chassis. As a result the beam thickness can be calculated by assuming a maximum allowable deflection of 0.02m. The following equations are from Beer, 2002.

- Moment of Inertia equation for a square cross-section: $I = \frac{1}{12}t^4$ where I is the moment of inertia and t is the width of the square cross-section.
- Maximum deflection equation for a uniformly loaded beam: $x = \frac{5wL^4}{384EI}$ where x is the absolute maximum vertical deflection, w is the total load force (total mass

times gravity), L is the effective length of the chassis, E is the Young's modulus of the material, and I is the moment of Inertia.

- Maximum horizontal force: $F = \dfrac{Ext^2}{L}$ where F is the maximum horizontal force, E is the material's young's modulus, x is the deflection, t is the width of the beam, and L is the total length of the chassis.
- Maximum deflection due to moment loading at the edge of the chassis: $x = \dfrac{ML^2}{9\sqrt{3}EI}$ where x is the maximum deflection in the chassis, M is the moment, L is the length of the chassis, E is the young's modulus of the material and I is the beam's moment of Inertia.

The last two equations are used to calculate the maximum allowable horizontal force and moment applicable to the chassis before failure. This provides a high level analysis of the chassis's ability to perform DRM 3 and DRM 4 operations.

Furthermore, this model does not assume the different types of dynamic failure modes, such as vibrations, horizontal, and dynamic loading. In addition, the chassis subsystem does not include stress concentration loads, especially at welds and interfaces. However, this model does incorporate an additional five percent of mass for design growth. For future works, this module can be integrated with MUSE to analyze what kind of loading forces will be experienced by the chassis while traversing on actual terrain.

The chassis module also assumes a stability grade of $\pi / 4$ since the LRV had a requirement to be statically stable on a 45 degree slope. The wheel factor is 1 for the camper. Furthermore, the track of the wheel is approximately 1.07 times the diameter of the wheel. The wheel base is then the maximum between the length of the crew compartment and (2 x (wheel diameter) + (distance between wheels)). In addition to these assumptions, the UPV chassis module assumes that it can hold up to four astronauts. The UPV chassis module also accounts for the human interfaces with the vehicle and its geometry.

Description

The chassis subsystem is consisting of square cross-section side rails and cross bars. The camper chassis currently has two side rails and three cross bars. The UPV chassis has three side rails (one additional rail in the middle) and three cross bars. This module also calculates the free volume left in the chassis and in the space between the structural shell and the bottom of the chassis. This free volume calculation is useful in allotting payload sample and equipment volumes.

The material of the camper and UPV chassis are currently a form of Ti-alloy. (Although this is the current material setting, the material type is actually a design variable. A wide range of material choices is provided by the material database.) Furthermore, both the camper and UPV chassis incorporated a 5% mass allocation for future design growth. The UPV chassis will have the ability to support construction and resupply operations.

Design variables

Design variables include the material selection for the chassis. The planet's gravity is also a design variable in this module. For the UPV, the number of crews on the vehicle is another design variable. In addition, the chassis is affected by the geometry and ladder configuration. The stability grade and the maximum allowable deflection are also parameters that the chassis needs to be designed around.

Options

Materials

Materials for the chassis may include: aluminum alloys, different types of steel, Titanium, magnesium alloy, carbon/graphite/glass or other types of composites.

Chassis geometry

In this module, the chassis is representative of a ladder chassis frame. There are however, many different options for chassis designs. For example, a chassis can be designed with a box frame or in an "I" shape. The cross-section profile of the chassis members can also vary in design. The different chassis members can be "I" beams, completely solid, have a hollow middle, and so forth.

The chassis can also be designed for interchangeable modules or it can be designed for integrated components. The former allows for a wider range of use for the chassis but will be more complicated to develop. Furthermore, a universal chassis design can be a baseline for multiple platforms. As a result, different consumables, such as power and water, can be swapped in and out of the chassis depending on the need and the mission. With a common chassis, DRM 1's, resupply, and logistic operations can take advantage of customizing consumables depending on the specific terrain traveled.

A foldable chassis design is also an option. A foldable chassis allows for easier transportation of the system but makes the system much more complicated. A uniform chassis is easier to build but might be more difficult to transport.

Design considerations

The current design chose to follow a ladder frame template because the ladder chassis provides excellent structural support from vertical loads and provides different compartments for the various other subsystems. The chassis module currently assumes the beams to be solid Ti-alloy beams. The simplicity of the beam geometry allows for ease of machinability. Furthermore, using Ti-alloy allows the chassis to carry the desired loads with little weight penalty. The disadvantage is that using Ti-alloy might result in high cost.

In addition, the UPV chassis is designed to be foldable. This makes the vehicle easier to transport. Although having a foldable chassis affects the total strength of the system, the chassis will have additional structural reinforcements especially at the joints. For simplicity, this model will consider that the foldable chassis will behave similarly to a solid chassis. In addition, the mass growth allocation for this system is five percent. Further work can be done on modeling the folding joint on the UPV chassis.

Interfaces

Inputs

The inputs for the structure subsystem primarily come from the human activity module. This includes the radius and length of the crew compartment. The wheel diameter and total mass (the chassis will have to support) are also important inputs. In addition, the external environment conditions are inputs to this module.

Outputs

The outputs of this module are total chassis mass, chassis volume, thickness of the chassis beams, wheel base, track and the free volume between the chassis and volume.

Interfaces

The chassis module interfaces directly with the human activities, payload, structures and propulsions. In addition, the chassis is affected by each of the other subsystem because the chassis will need to support the load generated by all the different systems, except propulsion.

Sensitivity to different planet environments

Analyzing how the structure subsystem will change in different planetary environments is fairly straight forward. The major factors that will affect this subsystem are the gravity on the different planets. The gravity will affect the structure of the chassis. The thickness or mass of the chassis scales with the intensity of the gravity. The terrain of the planet can also affect how much horizontal and vibration loads are placed on the chassis.

References

PSV code
Beer, Ferdinand et al. Mechanics of Materials, Third Edition, McGraw Hill, New York, 2002.

4.4.11 Structure subsystem

The structure subsystem in this design is the outer frame of the crew compartment. Hence, this subsystem is only applicable to the camper. The structure subsystem includes the shell and skeleton frame of the vehicle. The primary requirement of this subsystem is that it must keep the crew safe from the external environment under normal operations, contingencies and in an accident.

Assumptions

This model sizes the structural shell thickness on the pressure difference between the internal and external environment. This dimension does not include the volume needed for thermal insulation and radiation protection. The thickness of the shell (t) is calculated by the hoop stress relationship (Beer, 2002): $t = \frac{\mathrm{Pr}}{\sigma / sf}$ where P is the pressure difference between the internal and external environment, r is the radius of the shell, σ is the stress and sf is the safety factor (in this model it is set at 4).

Furthermore, this model does not assume the different types of dynamic failure modes, such as vibrations and dynamic radial loading. In addition, the structure subsystem does not include stress concentration loads, especially at the doors and interfaces. (Realistically, the wall thickness will vary and have to take into account stress points around airlocks, hatches, windows, equipment attachments, support and suspension for wheels, bending stresses due to terrain and concentrated loads from bumping, accidents, collisions and roll-overs.) However, this model does incorporate an additional five percent of mass for design growth. For future works, this module can be integrated with MUSE to analyze what kind of loading forces will be experienced by the structure while traversing on actual terrain.

Description

The shell is supported by a frame consisting of six horizontal support beams and four cross-section ribs. The beams and ribs have a 0.05m by 0.1m cross-section area. Furthermore, the cabin floor is assumed to have a thickness of 0.06m. In this model the number of supports and cross-section areas are based on airplane specifications. The floor thickness is also modeled from current vehicle designs. The internal crew compartment pressure is set at 10.2 psi (0.694 atm) for Moon and Mars operations. On Earth, this model assumes that the shell thickness is approximately 0.05m (this thickness is an approximation of a U-haul wall).

The skeleton frame material is currently Al-2219 and the shell material is Al-7075. Although this is the current material setting, the material type is actually a design variable. A wide range of material choices is provided by the material database.

Design variables

Design variables include the material selection for the shell structure and skeleton frame. The internal and external pressures are also design variables in this module. In addition, the structures are affected by the geometry and cross-sections of the skeleton frame. The thickness of the floor and the stress safety factors can also be modified within the code to accommodate for different loading conditions. Furthermore, this model allocates a five percent mass increase for design growth.

Options

Materials

Materials for the frame may include: aluminum alloys, different types of steel, Titanium, magnesium alloy, Carbon/graphite/glass or other types of composites. Materials for the shell may include: aluminum honeycomb, aluminum sheets or various composite materials.

Structural geometry

In this module, the structural shell design for the pressurized vessel will be the most important feature to look at. The shell can be any geometric shape given that it is transportable to its destination. For example, the shell can have flat walls, curved walls or both. However, in general, spheres, ellipsoids, and cylinders with spherical or elliptical ends are lighter per unit volume than shells with flat sides. Although shells with flat sides need more reinforced walls, they can provide more efficient external and internal packing space. Constructing a vehicle with flat sides also tend to be easier than a cylindrical vehicle.

Design considerations

Although there are different options for the structural geometry for the shell, this module selected to pursue a cylindrical design. The pressure differences greatly affect the thickness and overall mass of the vehicle. In order to minimize total system mass, a cylindrical geometry was chosen. The internal crew compartment is designed to optimize crew volume by allotting empty spaces for storage.

The environment interfaces is another area for trade analysis. Different options for interfacing with the environment include an inflatable airlock, slip-on EVA suits, detachable airlock module or an integrated crew airlock. The last option was selected because it is the most mass efficient solutions. The integrated airlock will also serve as the crew sleeping quarters thereby reducing the amount of total radiation shielding over the complete vehicle. Furthermore, this reduces a lot of the complexities that would have been involved in interfacing with an inflatable airlock or slip-on suit.

Interfaces

Inputs

The inputs for the structure subsystem primarily come from the human activity module. This includes the radius and length of the crew compartment. The floor width and the maximum vertical distance in the crew compartment are also inputs. In addition, the external environment conditions are inputs to this module.

Outputs

The outputs of this module are total structure mass, including the shell and skeleton frame, overall shell volume, the surface area needed for radiation shielding and the surface area needed for the thermal system.

Interfaces

The structure module interfaces directly with the human activities, thermal and radiation subsystems. The total structure geometry and mass is also used by the chassis subsystem.

Sensitivity to different planet environments

Analyzing how the structure subsystem will change in different planetary environments is fairly straight forward. The major factors that will affect this subsystem are the external environmental pressure and gravity. The external pressure will affect the thickness of the shell. The shell thickness scales directly with the absolute pressure difference, given the other variables in the hoop stress equation remains constant. Changes in gravity will affect the severity of loading on and by the structure.

References

PSV code

Beer, Ferdinand et al. Mechanics of Materials, Third Edition, McGraw Hill, New York, 2002.

4.4.12 Science Payload

The science instruments and tools carried on the vehicles are very closely based on work from the CER study. Table 20 and Table 21 show the mass breakdowns of the payload on the UPV and camper respectively.

Table 20: UPV science payload list

Time Of Flight-Mass Spectrometer	10	*kg*
Mars Organic Analyzer	11	*kg*
Spares and consumables	4	*kg*
Survey equipment	15	*kg*
Shovels, hammers, corers	30	*kg*
Atmospheric samplers	30	*kg*
Still/video cameras	20	*kg*
Hand lenses	2	*kg*
Aeolian sediment trap	5	*kg*
Rock sample holders	30	*kg*
	157	*kg*

Table 21: Camper science payload list

Drill (20 m)	*250*	*kg*
GC-MS (2)	*75*	*kg*
Optical microscope	*15*	*kg*
APXS	*5*	*kg*
X-ray fluorescence	*15*	*kg*
Amino acid, chirality analyzer	*11*	*kg*
Raman spectrometer	*8*	*kg*
Infrared spectrometer	*8*	*kg*
Solubility/wet lab	*20*	*kg*
Sample packaging/Glv. Box	*150*	*kg*
Computers	*15*	*kg*
Cameras	*10*	*kg*
Rock saw, grinder, sieves	*10*	*kg*
Metabolic analyzer	*15*	*kg*
Protein, DNA	*25*	*kg*
	632	*kg*

4.4.13 Vehicle Communications Model

The communications model built for the vehicle design is based primarily on sizing two link budgets: direct communications with TDRSS and surface communications.

Assumptions

The communications model incorporates the following assumptions:

1. The camper will carry two antennas: one for direct-to-TDRSS communications and one for surface communications.
2. The UPV will carry a single antenna for surface communications.

3. The antennas operate in the S-band frequency range; the low frequency helps minimize diffraction losses.
4. The user data rate is 1 Mbps (this represents the **total** bandwidth).
5. The link margins are 10 dB for direct-to-TDRSS and 20 dB for surface.
6. The effective antenna diameter for the direct-to-TDRSS antenna is 0.5 m and 0.01 m for the surface communications.

The gain for the TDRSS satellite in S-band was estimated to be 39.7 dB.

Mass Sizing

The antenna mass is based on spacecraft antenna mass sizing used in Darren Chang's Masters thesis [Springmann]. This sizing relation is based on Table 13-16 in SMAD:

$$Mass = 2 \times 9.173(Effective\ Antenna\ Diameter)^{1.403}$$

A factor of 1.5 was included to account for mounting equipment and other masses associated with including it on a surface vehicle. The communications hardware mass was assumed to be included in the avionics mass budget.

Power Sizing

The transmit power was found using the link budget analysis outlined in Chapter 13 of SMAD. It was assumed that the power required for communications was 1.5 times the power required for communicating (direct power and surface power for the camper, surface power only for the UPV).

Volume

It was assumed that antenna volume was not directly related to the vehicle design since the antennas would be mounted to the top of the vehicles. Communications hardware volume was accounted for in the avionics volume budget.

[Springmann] de Weck, O, Springmann, P.N., Chang D. "A Parametric Communications Spacecraft Model for Conceptual Design Trade Studies", AIAA-2003-2310, 21st International Communications Satellite Systems Conference, Yokohama, Japan, 15-19 April, 2003.

4.5 Vehicle selection

The UPV and Camper design specification for the Moon are fixed. Table 22 and Table 23 show the dimension, volume and mass of each subsystem of Camper and UPV.

CAMPER	dimensions (m)		vol (m^3)	mass (kg)
Crew compartment	radius	1.63		275
	length	3.11		
Comm.	antenna height	1		10
Chassis	wheel base	3.64		321
	wheel track	3.49		
	height	0.0755		
Avionics			0.248	200
ECLSS	O_2-N_2 tanks		0.0966	358
	H_2O tanks		0.1428	
Payload	equipment		0.53	482
Propulsion	wheel diameter	1.6		229
	wheel width	0.5		
Radiation	around shell			840
Suspension				355
Power	total		0.27	364
	water		0.151	
Thermal	vert. radiator		0.5281	226
	MLI		0.55	
	pump		0.06	
Samples			1	150
		Total Mass (kg)		3810

Table 22: The Lunar Camper Design Specification

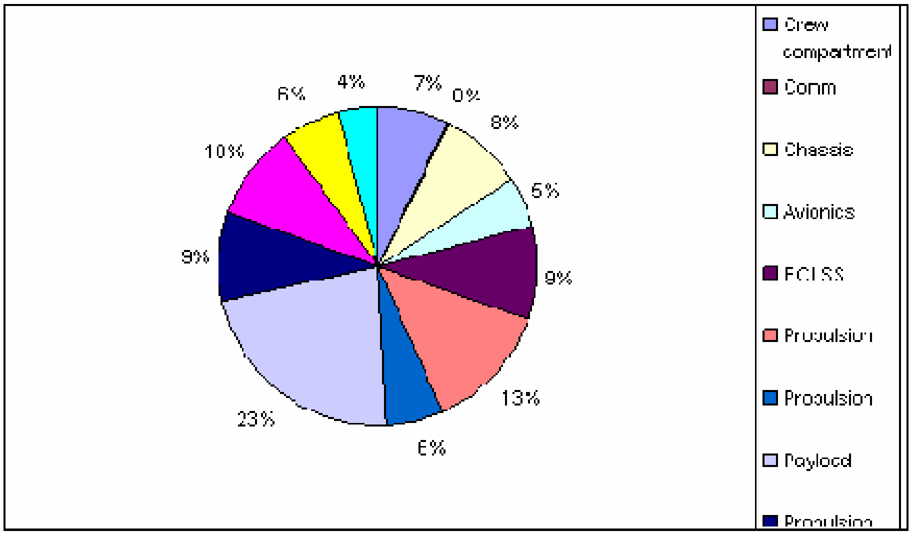


Figure 38: Mass distribution of Camper

Total camper mass is 3810 kg. This mass includes 482 kg of payload, which is science equipment, and 150 kg of rock samples.

UPV	dimensions (m)		vol (m^3)	mass (kg)
Chassis	**wheel base**	2.6		58
	wheel track	1.7		
	height	1.4		
Avionics			0.248	20
Payload	**equipment**		0.21	90
Propulsion	**wheel diameter**	0.7		48
	wheel width	0.23		
Steering				15
Suspension				69
Power	**total**	0.27		44
Thermal	**total**			12
Samples			0.1	30
		Total Mass (kg)		386

Table 23: The Lunar UPV Design Specification

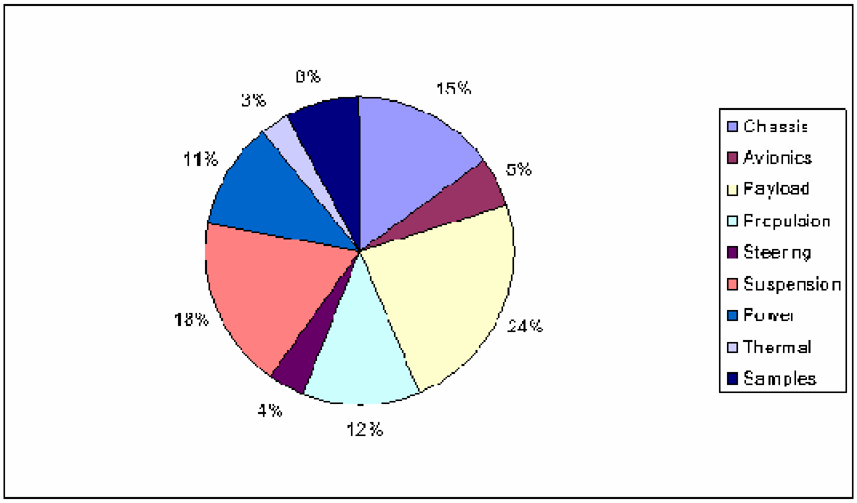


Figure 39: Mass distribution of UPV

Total mass of UPV is 386 kg including 90 kg of payload, which is science equipment, and 30 kg of rock sample. 2.6(m)*1.7(m)*1.4(m)

Table 24 shows power distribution of camper for each operation phase. The avionics, communication, and ECLSS always require power. When the astronauts drive a camper, propulsion, thermal, avionics, communication, and ECLSS are operated, but human activities module does not require power because every astronaut conducts EVA. When the astronauts do a science operation, thermal, avionics, communication, human activities, and payload (science) modules require power. In addition, ECLSS module generates water using the propulsion power. At night, system only needs power for thermal, communication, human activities, and ECLSS with generating water.

Camper (Watts)	**always**	**driving**	**science (day)**	**night**
Propulsion		1205		
Thermal		73	87	87
Avionics	300	300	400	
Comm	96	96	96	96
HA			150	150
ECLSS	80	80	900	900
Payload (Science)			100	
Steering				
sub Total	476	1754	1733	1233
Total with 15% margin	547.4	2017.1	1992.95	1417.95

UPV (Watts)	**driving**
Total with 15% margin	852

Table 24: Power distribution of Camper and UPV

4.6 Visualization, Geometric Design

Based on the vehicle design data (mass, geometry), drawings of the UPV and the camper elements were created using 2D-CAD. The primary purpose of geometric design was to provide a baseline concept for the geometrical arrangement of vehicle subsystems, a comparison of the UPV and camper in size and shape, demonstration of UPV / camper interfacing for DRM-2, and documentation for efficient visual communications of our architecture choice and operations concept (also suitable for future outreach activities). The design concepts for the camper and UPV presented here naturally only represent two possible instances; a comprehensive analysis of geometrical designs using 3D virtual mock-ups was beyond the scope of this project and is considered part of future work.

4.6.1 UPV Geometric Design

The UPV is intended both as an independent vehicle for short-range exploration and scouting, and as a guiding vehicle for the camper for long-range traverses. Also, the UPV is intended for use during lunar sortie missions, and therefore has to be transportable within the human lunar lander cargo capacities (transportation constraints on the UPV design for the Earth analog use case were eliminated by choosing the use of regular ATVs as a UPV substitute). Although the UPV is nominally used only with 2 crew it needs to be capable of transporting 4 crew (and no exploration cargo) in an emergency.

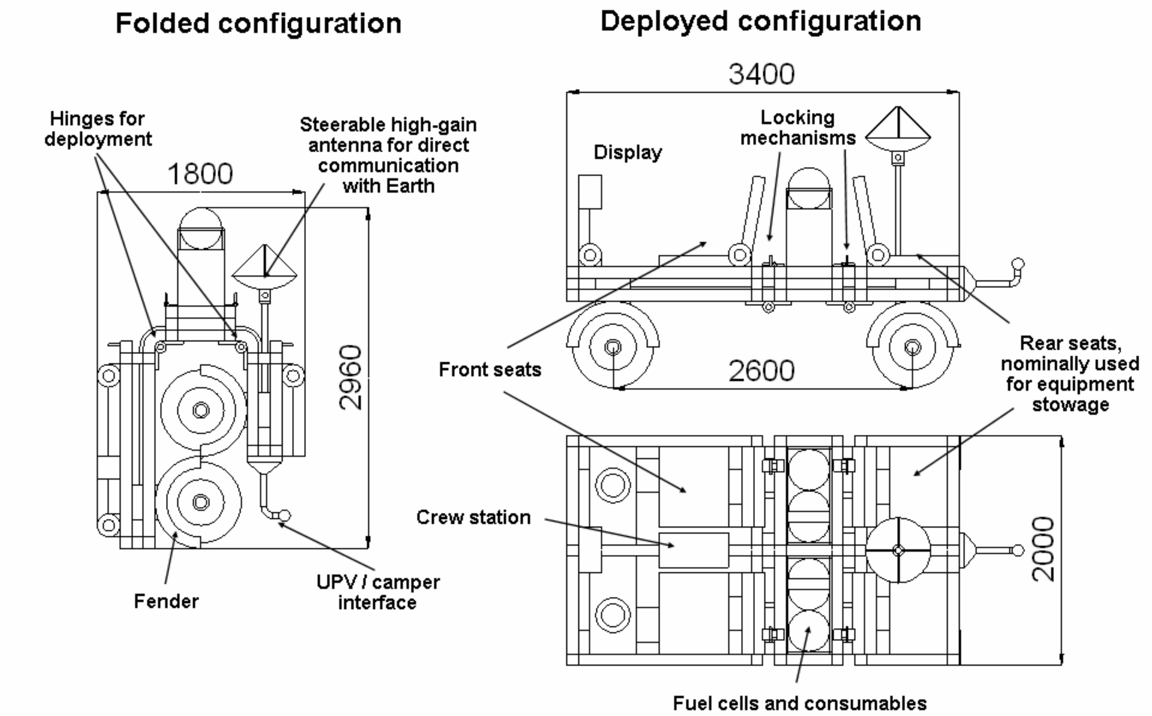


Figure 40: Annotated drawings for the Unpressurized Vehicle (UPV); side view folded position, side view deployed position, top view.

Figure 40 provides drawings for the UPV created using a 2D-drafting program. The UPV is shown in side view (folded and deployed position) and top view. The UPV chassis is divided into three frames which are connected serially using hinges and (in the deployed position) a locking mechanism; the configuration is intended to be deployed once. The weight force together with the locking mechanism ensures that the chassis stays deployed (self-helping mechanism); thus no springs or active control are required. Also, the wheels do not have to be folded in (as for the Apollo LRV), resulting in a significant reduction in complexity compared to the LRV. In the folded configuration, the UPV requires a volume envelope of 1.8 m x 3m x 2m; this should be within the cargo envelope pf the human lunar lander. If a significantly smaller envelope is required, the vehicle could potentially be disassembled at the hinge joints and stowed in pieces aboard the lunar lander. This would, however, also require a one-time reconnection of power to the front wheel drive motors from the fuel cell units on the lunar surface because the fuel cell power plants are located in the middle chassis unit.

The chassis serves as "bus" elements that nearly all other elements of the UPV interface with. The front chassis section is connected to the suspensions for the front wheels, and provides crew displays, a crew station for vehicle control, two seats for primary accommodation of astronauts, and capacitive thermal control units under the seats. These units store waste heat for the duration of one EVA. After conclusion of the excursion, the front seats are rotated up, and the thermal radiator dust covers removed so that the radiators can dissipate heat to space.

The middle chasses section serves as connecting element for the front and rear chassis elements and also houses the fuel cell power plants with associated consumables storage (hydrogen. oxygen). Power is generated in the fuel cells and then fed to the drive motors through electrical connections along the chassis frames. The rear chassis provides another two seats which house crew gear and scientific instruments during nominal operations. In a contingency situation, these items are offloaded and the two spare seats would be occupied by two additional crew members. The rear chassis also houses communications equipment for direct communications to Earth via a steerable high-gain antenna. It also provides attachment for the UPV / camper interface.

4.6.2 Camper Geometric Design

Given the mass and geometry data from the design analysis, a conceptual design was created for the planetary camper with focus on the lunar version. As for the UPV, it is necessary to stress that a comprehensive analysis of the configuration space was beyond the scope of the class design effort. Figure 41 provides an overview of the camper design with back and side view drawings.

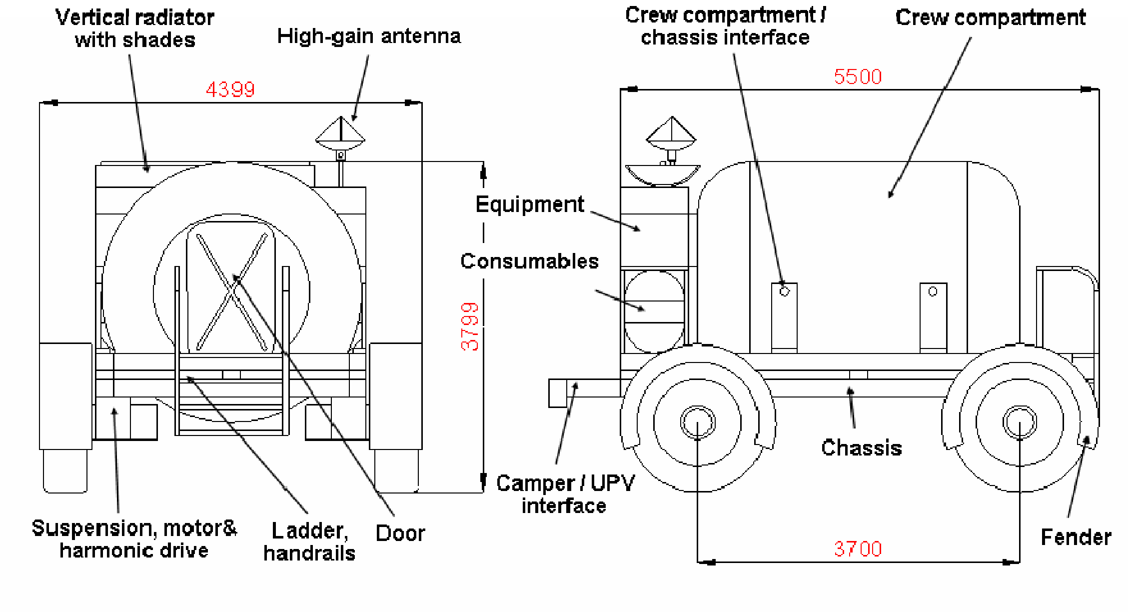


Figure 41: Camper drawings, back and side view

The camper design is fundamentally different from the UPV because it includes a crew compartment that provides a shirtsleeve environment for the crew for intra-vehicular operations and regeneration between driving periods and exploration EVAs. The original preferred crew compartment form was cylindrical with a radius of 1.63 m; as the ESAS LSAM crew compartment was baselined with a 1.5 m radius, the camper crew compartment radius was adapted to 1.5 m in order to enable commonality of the two crew compartments. This commonality might provide an interesting option for reducing development work required and should be investigated further.

Like the UPV design, the camper features a chassis which serves as “bus” element with interfaces to most of the other subsystems. The chassis is directly connected to the suspension and drive systems for the four wheels. The chassis also serves as attachment point for the cradle-like mechanism that provides attachment for the crew compartment; this attachment method was modeled after the attachment of modules in the space shuttle payload bay.

Directly attached to chassis is also an equipment module which provides subsystem equipment for communications, thermal control, fuel cells for camper drive power, hydrogen, oxygen, and water storage, and attachment for the vertical thermal radiator and the steerable high-gain antenna. The radiator features a sun-shield in order to eliminate heat input from the lunar surface into the radiator.

Attached to the chassis is also the camper part of the UPV/camper interface; Figure 42 shows the connected configuration for DRM-2 traverses:

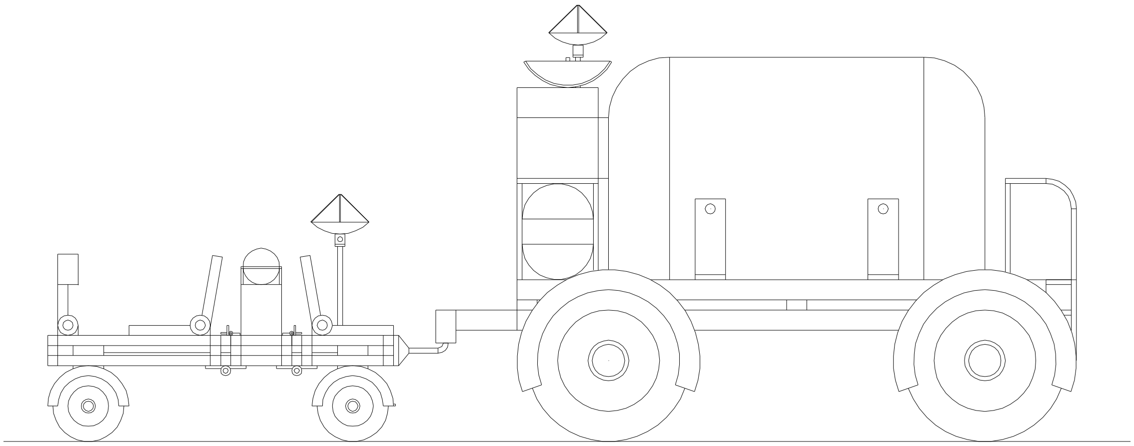


Figure 42: UPV–camper DRM-2 traverse configuration

Larger versions of the drawings presented here can be found in the Appendix for this section (see below).

5. Integrated Dynamic Capability Analysis

5.1 Overview

The Mission Utility Simulation Environment (MUSE) is a simulation tool that takes the vehicle design parameters and evaluates the performance of the design on representative terrain on the planetary surface.

In Chapter 3, the architectural selection had two metrics that were used to determine the optimal architecture: vehicle wet mass and number of science sites that could be visited. The vehicle design model was able to provide a mass estimate, and MUSE calculates the total number of sites that can be visited for both DRM-1 and DRM-2 operations. Over the course of the project, MUSE evaluated the vehicle point designs on lunar terrain only; future work could include Mars and/or Earth.

MUSE provides three main benefits to the vehicle design process. First, the vehicle model uses various static assumptions about the average or worst-case quantities that will be encountered on the planetary surface, such as slopes or power draw under certain situations. MUSE aims to add a dynamic analysis capability, whereby the consumable use is dependent on local terrain as the vehicles move across the lunar landscape.

Second, the results of MUSE will also provide valuable feedback to the vehicle design team. It may be that the vehicle design did not fare as well as anticipated on the representative terrain. This can either be attributed to issues in the code or unanticipated terrain effects. MUSE can aid the vehicle design team in generating better point designs.

Finally, the results could point to modularity opportunities for consumable storage, especially between the camper and the UPV for different missions. Strategies for storing consumables in easily swappable chunks may become apparent when the vehicle design is run over many missions in different terrain environments.

This chapter provides an overview to the MUSE methodology and the results when MUSE was run with the latest point design provided by the vehicle design team.

5.2 Methodology

The MUSE model incorporates several methods and sources of data in order to simulate, to a reasonable degree of accuracy, operations on the lunar surface. The following section details the main methods used to simulate exploration on the Moon.

5.2.1 Exploration Strategy

Exploration of nearby sites on a DRM-1 is modelled by starting at a geolocated origin point and visiting science locations. The locations are uniformly distributed within a square grid 40 km on a side (the maximum radius of a DRM-1 is 20 km), and on average the science locations are roughly 3 km apart. Each has a coordinate relative to the origin point, and when coupled with the known latitude and longitude of the origin, one can determine the lat/lon coordinate of the location of interest.

Using this grid, we manually generated 24 excursion plans, where the vehicle would start at the origin point in the middle of the grid and travel to a pre-defined sequence of locations. These 24 excursions are of four types, as shown in Figure 43, which capture a broad range of exploration strategies:

- **Spiral**: a local survey of the immediate surroundings, where the astronauts investigate sites around to the origin point and progressively move further away.
- **Loop**: the astronauts visit sites in a roughly straight line away from the origin point, and return on a different straight line.
- **Area Search**: a survey of a more distant area, where the astronauts travel to a site further away from the base (10 to 15 km) and investigates sites close by before returning to the origin point.
- **Grid Search**: a sequence of straight-line traverses to explore a section of the surrounding area.

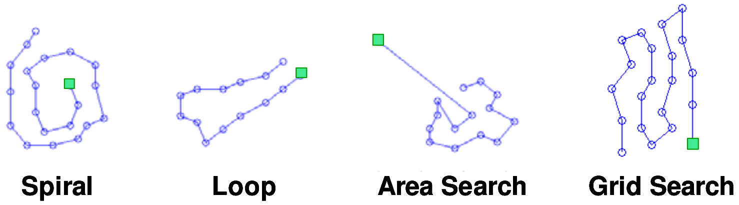


Figure 43: Search Patterns

Each location of interest on a DRM-1 excursion can be one of two types: a “site”, which represents a single point of interest, and a “region”, which contains a collection of four sites close together. In the MUSE model, astronauts would spend between 30 to 45 minutes at a site, and between 2 and 3 hours at a region (or four times the duration of a single site).

A DRM-2 excursion consists of the camper starting at the outpost and travelling 100 km to a campsite, where the camper is parked. The campsite becomes the new origin point and the DRM-1 excursions are performed starting from camp.

5.2.2 Statistical Sampling

In scenario-based modeling, the results are highly dependent on the assumptions and properties of the scenarios that were run, such as the terrain over which it is performed and the site distribution used. The objective becomes to abstract out as much of the dependence on site selection and terrain as possible.

For the purposes of this project, which introduces MUSE as a proof of concept, only a small number of sample points were collected. These points provided variation in the scenarios conducted by changing the following parameters:

1. *Exploration strategies* (the 24 excursions mentioned in the previous section)
2. *Science site types* (“site” vs. “region”)
3. *Operations within a region* (walking vs. driving between sites)
4. *Origin locations* (five for DRM-1)

5. *Habitat and camp locations* (ten for DRM-2)

There were 360 total sample points for DRM-1 operations, and 10 for DRM-2 operations. Missions were assigned for both DRM-1 and DRM-2 operations. For each DRM-1 mission, all 24 excursions were run.

A DRM-1 mission consists of:

1. Choosing whether the science site is a single site or a region.
2. If the science site is a region, whether the astronauts walk or drive between sites
3. The location of the origin.

A DRM-2 mission consists of the habitat and camp locations between which the campers and UPVs travel.

The eventual goal is to create a surface mobility operations equivalent of an aircraft V-n diagram to provide an indication of the envelope of capabilities of the mobility system across a number of logistical scenarios. However, to create such a diagram, a significantly larger sampling would be required.

Terrain Map

The terrain elevation data used was a Digital Elevation Map (DEM) of a highland area west of Tsiolkovsky Crater on the far side of the moon (110E-117E, 16S-23S) as shown in Figure 44. The data was generated using imagery taken by stereo cameras mounted on the Service Module of Apollo 15. This area was selected because it had one of the most accurate elevation data sets. In this DEM, one pixel represented a square approximately 210 m on a side, and the elevation resolution was 39 m. This compares to most lunar DEM data that has 1 km pixel resolution and 75 m elevation resolution.

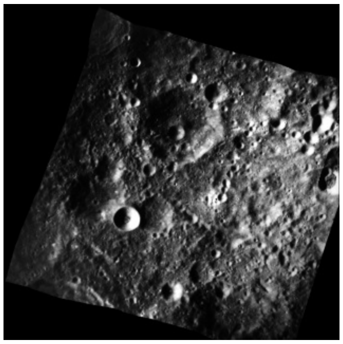


Figure 44: Highland west of Tsiolkovsky Crater

Coupled with the terrain data is an estimation of two factors. First, the *meander factor* (MF) is a factor that determines how much distance is actually travelled compared to the actual distance between two points. This was estimated by evaluating the average change between a pixel and its surrounding pixels. Second, the *speed factor* (SF) is the fraction of the maximum speed allowed. It is modelled as an inverse square relation to the meander factor: $SF = 1 / MF^2$. This relation was based on experience from the Maine-Moon-Mars analogue excursion.

5.2.3 Propulsion Model

While on a traverse, MUSE determines the instantaneous power consumption required to propel the vehicles over the terrain. A propulsion function was created by modifying several modules from the existing PSV software. The function calculates the drive power required based on the speed at which the vehicle drives, the grade in the direction of travel, loaded vehicle mass, vehicle parameters (wheel diameter, number of wheels), and the environment parameters (soil properties, gravity). Table 25 shows the output of the model based on the selected inputs:

Mass	Slope	Speed	Wheel Diameter	Wheel Width	Number Wheels	Drive Power Required
1000 kg	10º	5.0 m/s	0.7 m	0.2 m	4	1325 W

Table 25: Sample inputs and outputs of the internal Propulsion model

5.2.4 Constraints and Drive-Back

MUSE is designed to guarantee that vehicles always return to the origin point, which is either the camper or base for DRM-1, or the base for DRM-2. This is enforced by drive-back constraints on the total EVA time and energy storage onboard the vehicles, although life support consumables could be included in the future.

A constraint is considered violated if there would not be enough time, energy, or other consumables remaining to drive to the next site, explore, and return to the origin. If a constraint is violated, then MUSE "drives" the vehicle back to base. The vehicle can either take the straight-line path back to base, which assumes worst-case terrain properties (since terrain on this path is unknown), or it can drive back over the path it took (with known properties). The drive-back decision chooses the path that takes the least amount of time, and increments the time and decrements the consumables accordingly.

5.2.5 DRM-1 Modelling

A DRM-1 consists of starting at the origin point and travelling to a pre-defined set of science sites as described in the *Exploration Strategy* section. Between each site, MUSE calculates intermediate points, or "chops", spaced every 200 m. At each of these chops, the travel distance, speed, average slope are accessed from the map data, and the time to traverse the chop is computed by dividing travel distance by speed. Based on the data of the chop, the required propulsion power and the total energy consumed (power draw × time) are computed. This energy is decremented from the onboard fuel supply, and the total time on EVA is incremented. This continues until the vehicle reaches the site.

At each site, the vehicle does not consume power, but EVA time elapses and samples are collected at a constant rate of 18 kg/hr, which is based on Apollo sample collection [R]. The time spent at a site is a uniform random variable between 0.5 to 0.75 h. When the site time expires, MUSE checks the constraints to determine if the vehicle can reach the next site and have enough energy and time to return. If so, the vehicle starts another traverse to travel to the next site, and if not, the vehicle drives back.

5.2.5 DRM-2 Modelling

A DRM-2 excursion consists of two parts: the traverse from the hab to the campsite and exploration of the campsite. During the traverse to the campsite, the code keeps track of three main quantities for the five vehicles (3 UPVs and 2 campers):

1. *Camper energy supply*
   Both the campers and the UPVs that tow them draw power from the energy supplies onboard the camper during the excursion. As the vehicles move along the terrain, MUSE calculates the required power and decrements the camper energy storage accordingly.

2. *Lead UPV energy supply*
   One of the three UPVs travels ahead to scout the terrain and is not connected to the camper power supply. When the energy stores on the lead UPV are exhausted, all vehicles stop and the UPV is refuelled by the camper.

3. *EVA time*
   When the total time of travel reaches 7 hours, all vehicles stop and the astronauts rest for 17 hours. During this time, the camper draws power from onboard supplies but the UPVs are turned off.

Once the UPVs and campers have reached the campsite, the campsite represents the new origination point, and DRM-1s are conducted. The modelling of the DRM-1s at the campsite is the same as described in the previous section.

5.3 Integration with Vehicle Design

MUSE provides the ability to evaluate a point design from the vehicle model on representative lunar terrain. MUSE takes as inputs the mass and energy capacities of each vehicle and simulates exploration operations in terms of the amount of energy required to traverse the terrain between science sites. The results show how capable the vehicles are to perform DRM-1 and DRM-2 operations in terms of onboard consumables. Ideally, an iteration would occur where the vehicle design team would analyze the results from MUSE and adjust the vehicle design to improve performance. One such iteration was conducted over the course of this project and is described below.

5.3.1 Design Iteration Case Study

Our team was able to perform two design iterations with the vehicle model and MUSE; that is, the outputs of the vehicle model were fed into MUSE, after which the teams convened and discussed how the design should be improved for the next run.

After the first iteration, MUSE output data provided two observations. First, the energy capacity onboard the UPV for use on DRM-1 was far too high: over all the runs performed, the fuel used never exceeded 25% of capacity, meaning the UPV was carrying too much fuel. Second, the camper had insufficient energy to reach the camp: by the time it reached the site at which DRM-1s were to be performed, there was not enough remaining fuel to make it back to base, let alone stay at the camp to explore.

This provided valuable data to the vehicle design team that prompted them to modify their code. For example, some power-consuming units were removed and the power consumption profile was re-evaluated to be more realistic. As well, they made some modifications to the vehicle designs: the energy capacity was increased on the camper and decreased on the UPV. Another run of the vehicle model was performed, and these modified designs were input into MUSE for the final analysis.

5.4 Current Limitations of MUSE

The conclusions to be discussed in the following sections are based on the results of the model, which currently uses various internal assumptions to calculate the capability of the vehicle design. The results should be interpreted with these limitations in mind.

5.4.1 Surface Location

The map data used was of Tsiolkovsky crater, which is on the far side of the Moon. The data set was selected due to the difficulty of obtaining other, high-resolution maps. It is unlikely that this location will be visited on a lunar mission, so the vehicle is being assessed in MUSE on terrain that does not necessarily reflect the terrain on which will actually perform. Although using actual lunar data increases the fidelity of the analysis (rather than simple average quantities), future iterations should use map data of sites where lunar missions will be performed.

5.4.2 Map Resolution and Slopes

The elevation in the lunar maps used in MUSE is known at points spaced roughly 200 m apart. When the slope is calculated between two points, it determines the average grade between two points, and this is fed into the propulsion module. Although this may represent the overall average change in elevation from one point to the next, this approach cannot capture smaller hills as shown in Figure 45. This could significantly change the actual propulsion power requirements.

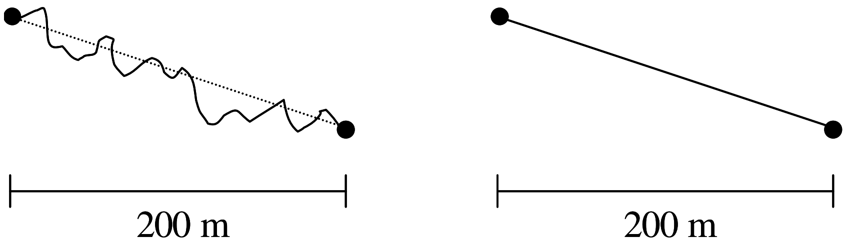


Figure 45: Actual elevation profile between data points (left) and MUSE internal representation (right)

5.4.3 Propulsion Modeling

The propulsion model, as adapted from PSV, currently assumes a constant speed on a constant slope for each 200 m traverse chop. Braking and acceleration due to more fine undulations in the terrain are accounted for by a simple factor of 2 on the drive power. A higher fidelity model of these two processes should be implemented in the future.

5.5 Sample Analysis Outputs

This section provides an overview of the results of the MUSE simulation of the planetary surface mobility system.

5.5.1 DRM-1 Energy / Payload Capacity Performance

Three consumables were tracked during the simulation of the DRM-1 missions: energy, sample payload mass, and sample payload volume.

Figure 46 is the Cumulative Distribution Function (CDF) of the energy capacity remaining on each UPV once the vehicle has returned to base. The distribution is calculated using all 360 DRM-1 excursions that were sampled. The CDF shows that each UPV consumes at least 30% of the available energy capacity on an excursion. Also, if the safety margin on the energy consumption were 15%, there is a 6% chance that the UPV would consume some of the safety margin by the time it returns to base.

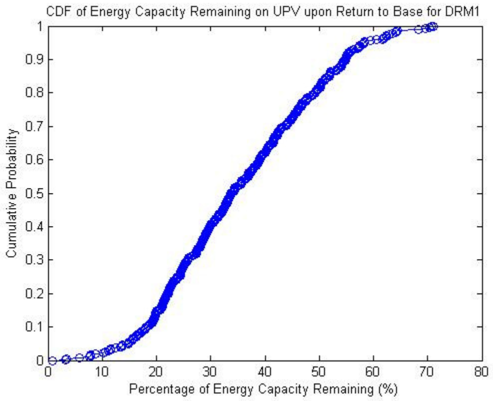


Figure 46: CDF of Remaining Energy on UPV for DRM-1

Figure 47 shows the CDFs for the payload mass and volume capacities remaining on each UPV once the vehicle has returned to base. There is a 30% chance that the UPVs will use up the sample mass capacity, but there is always at least 77% of the sample volume capacity remaining. These results suggest that the UPV design should be modified to increase the payload mass allowance and to consider decreasing the payload volume capacity, since it is never used up.

The two CDFs have the same shape due to the relationship between the sample mass and volume collection rates. The mass rates were estimated from the Apollo missions and the volume collection rates were found using the mass rate estimate and the average bulk density of the moon. Since the underlying variables are related, the shapes of the CDFs are also related.

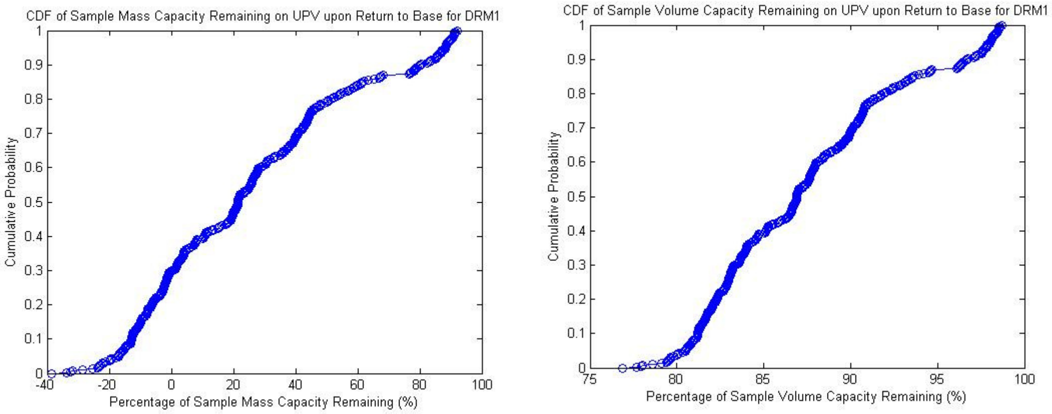


Figure 47: (a) Payload mass capacity CDF, (b) Payload volume capacity CDF

5.5.2 DRM-1 Drive-Back Conditions

Over all DRM-1 excursions, approximately 70% of the excursions ended because the vehicles were running out of energy, rather than exploration time (which constituted the remaining 30% of the excursions). This implies the operational envelope of the vehicles is most constrained by energy.

Also, at the end of almost every excursion (98%), the vehicle drove back to base on a straight-line path rather than over the path already traversed. This could be due to the exploration patterns, as vehicles may perform very winding paths to visit many sites, so the total distance traveled is much longer than the eventual straight-line path to base at the end of the excursion.

5.5.3 DRM-1 Metric and Results

The DRM-1 excursions were evaluated to determine vehicle performance in terms of the number of science sites that could be explored, since this metric directly relates to the overall value-generating process of exploration. The vehicles were also designed assuming a certain range (distance to furthest site and back plus some margin for meandering). This section details the results in terms of the number of sites visited per excursion and the effective operational range of the vehicle.

Figure 48 shows the Probability Density Function (PDF) for the number of sites visited per excursion over all the sampled missions. There appears to be a bimodal distribution: one hump occurs at about 4-5 sites visited per excursion, and the other occurs over 9 sites per excursion. This is due to the two types of science locations that the UPVs visit: single sites and regions. The vehicle can visit more sites if the locations are regions because the vehicle has to travel shorter distances to reach clusters of sites, so the peak on the right of Figure 48 represents visiting regions, where the left peak is visiting single sites.

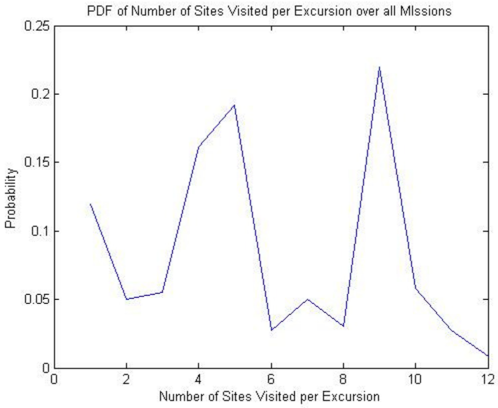


Figure 48: PDF of number of science sites visited per DRM-1

The overall expected value is 5.71 sites visited per DRM-1, with a standard deviation of 3.02. The large standard deviation is an artifact of the bimodal distribution.

5.5.4 DRM-1 Range

A histogram of the achieved range, or total distance traveled, for DRM-1 activities over all missions and excursions are shown in Figure 49. As before, the distribution is bimodal, though it is not nearly so distinct as for the number of sites visited. The UPVs were designed assuming an operational range of 60 km, but the results show the average distance traveled on a DRM-1 is only about 30 km.

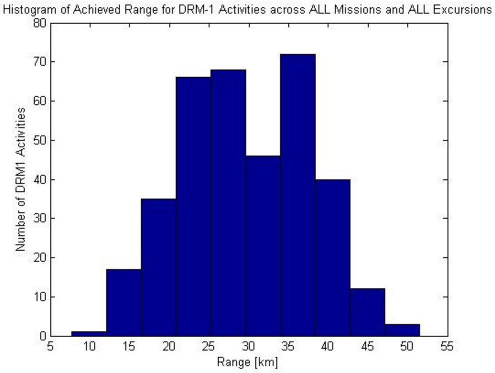


Figure 49: Histogram of DRM-1 range

5.5.5 DRM-2 Energy Storage

The DRM-2 missions are evaluated in terms of their capability to enable DRM-1 exploration activities, which is the primary value-generating capability of the camper vehicles. This is determined by the amount of energy available for exploration onboard the campers when they reach the campsite.

Figure 50 shows the energy available to perform DRM-1 varies dramatically for each DRM-2 mission analyzed. The worst-case DRM-1 energy available is only 2×10^8 J, and the best-case energy available is over 8×10^8 J, or 4 times as much as the minimum. This result is due to the variation in terrain that the vehicles must traverse in order to travel to the campsite.

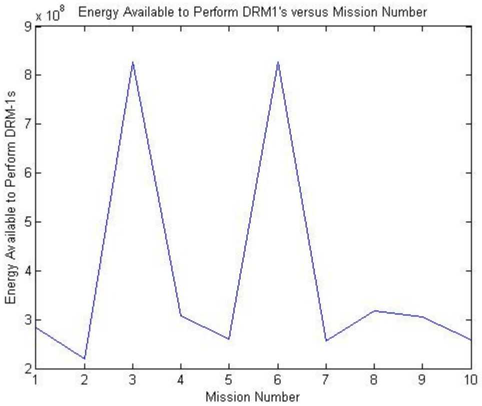


Figure 50: Energy available on camper for DRM-1 exploration

5.5.6 DRM-2 Metric and Results

The metric used to determine the performance of the campers on DRM-2 is the number of DRM-1s that can be performed when at the campsite. To calculate this, the UPV energy PDFs from DRM-1 were combined with the energy remaining data to determine the number of DRM-1s that are possible given the energy capacity of the campers.

The results shown in Figure 51 show that there is a 40% chance not being able to perform any DRM-1s, which means the vehicles must turn back immediately after reaching the campsite without exploring. There is a 40% chance of performing one DRM-1, and a 20% chance of performing two DRM-1s (with the small possibility of a third).

This distribution suggests an expectation of 0.8 DRM-1s per DRM-2, with a standard deviation of 0.75. The vehicle architecture was designed to be able to perform 3 DRM-1 exploration activities per DRM-2, so the results have several possible explanations. First, the camper vehicle may be under-designed. Second, one of the current limitations in MUSE is creating an over-constrained energy profile. We would suggest that the next iteration of the camper design contain more energy onboard, as well as additional work on MUSE to resolve some of the aforementioned limitations.

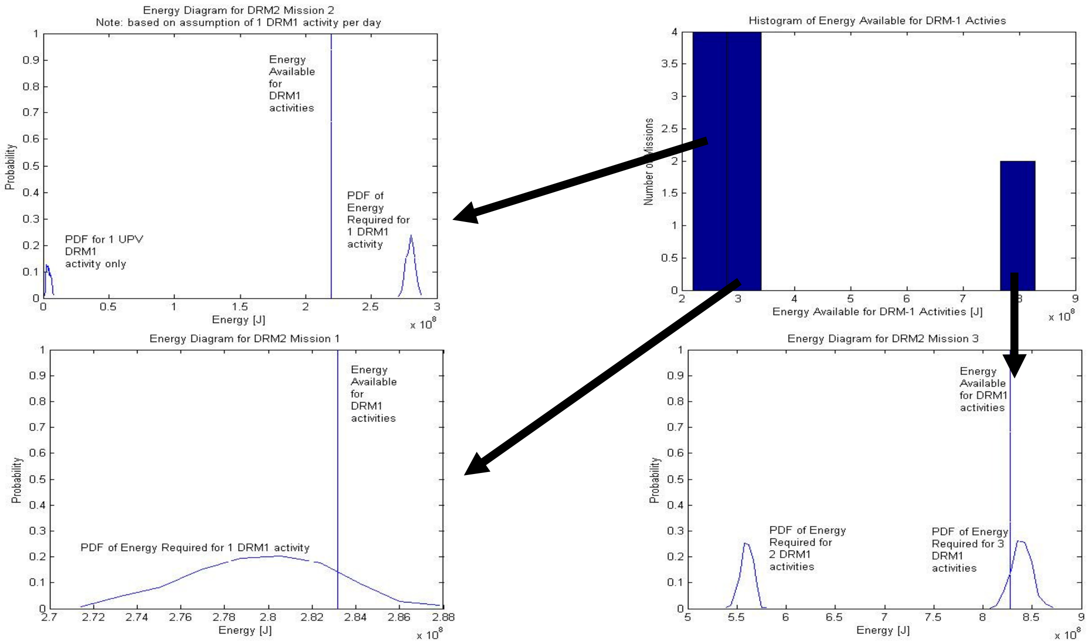


Figure 51: PDFs of the possible number of DRM-1s per DRM-2

5.6 *Modularity Opportunities*

One of the goals of this project was to identify opportunities to introduce modularity into the design. This section details a few of these opportunities highlighted by MUSE.

5.6.1 Modularity of Vehicle Energy Supply

One opportunity highlighted by MUSE is to consider the possibility of storing the energy consumables for the vehicles in modular, easily swappable containers. Creating modular energy supplies is a benefit in two respects.

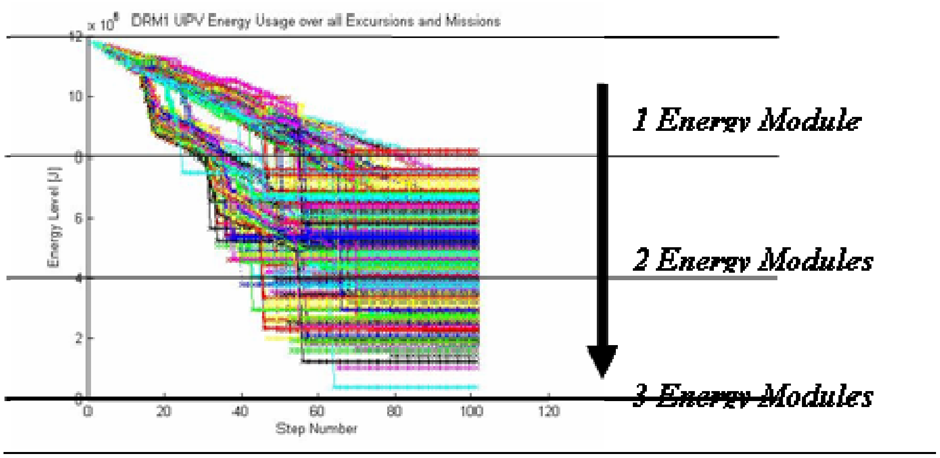


Figure 52: UPV energy use and possible modularization strategy

First, it would be possible to better match the energy requirements of the DRM-1 excursions to the energy capacity stored onboard. The variation in the energy usage over the different excursions and missions is considerable. Figure 52 shows the possible breakdown of energy storage according to the energy consumption curves of all excursions analyzed in MUSE. Carrying less energy translates to less mass which would make the UPVs more fuel-efficient, or the astronauts could use the extra space to store more samples.

Second, it is an area of potential commonality among vehicles. Modular energy storage could be very useful on the long DRM-2 missions, during which it was found that the lead UPV would need to be refueled at least twice on the way out to camp and twice again on the way back. Modular energy storage could enable astronauts to easily swap used energy storage modules for full ones to quickly resupply the UPVs.

5.6.2 Modularity of ECLSS Supplies

Modularity opportunities also exist for the ECLSS supplies, although the current version of MUSE does not track these consumables. Modular ECLSS supplies could potentially extend the excursion capabilities in some instances. For example, the missions that violated the time constraint did so because the time constraint was a simple way of capturing the availability of the ECLSS consumables. Additionally, modularity in the ECLSS supplies would enable easy reallocation of supplies as necessary, for nominal operations as well as in contingency situations.

5.7 Results Summary

Mission	Metric	Average	Std. Dev.
DRM-1	Number of sites visited per DRM-1	5.71	3.02
DRM-2	Number of DRM-1s performed per DRM-2	0.80	0.75

The camper needs more energy to allow the designed number of three DRM-1 excursions to be performed per DRM-2 mission. Please note these conclusions are subject to the limitations discussed previously.

5.8 Future Work and Extensibility

MUSE was constructed to be as extensible as possible. Here are a few ways that MUSE can be extended in the future:

3. Extend the analytical framework to include Mars and Earth.
4. Incorporate more logistics, as well as communications and navigation
5. Incorporate terrain data for the entire planetary surface to improve sampling.
6. Extend to include ECLSS consumables (the structure is already in the code).

As well, future work should strive to resolve some of the limitations of MUSE as described in previous sections.

[Cook] Anthony C. Cook, “Lunar Digital Elevation Models”
http://www.cs.nott.ac.uk/~acc/dems.html, web site.

[Surface Journal]: NASA, “Apollo Lunar Surface Journal”, http://www.hq.nasa.gov/office/pao/History/alsj/frame.html, web site.

6. Commonality with Earth and Mars Mobility Systems

6.1 Commonality, sensitivity, extensibility for different environments

The commonality and extensibility of the camper and UPV was analyzed using the PSV model developed prior to this project. The PSV model was used because of the general assumptions it made about Earth and Mars terrain. Terrain profiles and soil characteristics are needed in the TVM propulsion module. However, these inputs were not sufficiently available for the TVM to produce Earth and Mars point designs. As a result, the PSV model was used to provide specific point designs for the Moon, Earth, and Mars. Although the PSV is not as detailed as the TVM, it does provide an overview of the scaling affects the environment will have on the mass of the subsystem. (The differences between the PSV and TVM models were explained in the vehicle design sections.) It is important to note that multipliers and percentage of mass changes need to be analyzed to gain insight into vehicle commonality and extensibility. Looking at the multiplier or subsystem mass separately does not provide the complete picture of the design's extensibility.

Variables

The table below provides a list of the subsystems that will be affected the most by changes in planet environment. The environment will have varying affects on each of the subsystem. For example, the chassis subsystem will be scaled mainly by the gravity on the planet while the power unit will change depending on the temperature difference between the system and outside environment. Although the table lists the major subsystems that are correlated with the environment, not all of them, for example the radiation subsystem, were modeled by PSV.

Table 26: Requirement change related to planetary environments

System	Earth	Mars
Chassis	Gravity (9.8 m/s^2)	gravity (3.3 m/s^2)
ECLSS	breathing-air ventilation	CO2 control
Human activities	no airlock	similar to Moon
Propulsion	terrain and gravity	terrain and gravity
Radiation	none required	thickness, environment
Shell structure	external pressure	external pressure
Power	temperature difference	temperature difference
Thermal	heat absorption, convection	heat absorption

PSV Camper

The following table summarizes the changes in subsystem mass when designing a camper for different planets.

Table 27: Sensitivity analysis using PSV (1)

PSV Camper	Mass (kg)	Ratio	Absolute Difference (kg)

	Moon	Earth	Mars	Mars/ Moon	Earth/ Moon	Moon-Earth	Moon-Mars
crew station	1239	816	1238	0.999	0.659	423	1
communication	32	32	32	1	1	0	0
Chassis	109	268	219	2.009	2.459	-159	-110
Wheel	44	91	102	2.318	2.068	-47	-58
Suspension	160	150	190	1.188	0.938	10	-30
drive system	28	107	62	2.214	3.821	-79	-34
Power	113	136	207	1.832	1.204	-23	-94
Thermal	75	67	87	1.16	0.893	8	-12
Steering	22	20	23	1.045	0.909	2	-1
TOTAL	**1822**	**1687**	**2160**	**1.186**	**0.926**	**135**	**-338**

On Earth, the subsystems that vary the most from the Moon design are the crew station, chassis, and propulsion. The Earth crew station will be significantly lighter than the Moon design because the Earth camper will not need an airlock. The Earth gravity effects will greatly increase the chassis mass and the Earth terrain and soil parameters will affect the drive system, wheel sizing, and suspension.

The Mars design differs from the Moon design primarily in terms of chassis structure, propulsion, and power design. These subsystems will be affected by Mars' gravity, terrain characteristics, and temperature ranges.

In most of these subsystems, the bounding design will be for Mars. Mars almost always incur the most massive design, except for the Earth chassis and drive system. However, the vehicle masses for the different environments do not vary significantly. The Mars camper is 1.186 times more massive than the Moon design. On the other hand, the Earth camper is only 0.926 times the mass of the Moon design.

PSV UPV

The following table summarizes the changes in subsystem mass when designing an unpressurized vehicle (UPV) for different planets.

Table 28: Sensitivity analysis using PSV (1)

	Mass (kg)			Ratio		Absolute Difference (kg)	
PSV UPV	**Moon**	**Earth**	**Mars**	**Mars/ Moon**	**Earth/ Moon**	**Moon-Earth**	**Moon-Mars**
communication	16.21	16	16	0.987	0.987	0.21	0.21
chassis	32.74	194	65	1.985	5.925	-161.26	-32.26
wheel	11.16	54	63	5.645	4.839	-42.84	-51.84
suspension	11.23	39	23	2.048	3.473	-27.77	-11.77
drive system	10.73	47	21	1.957	4.38	-36.27	-10.27
power	20.52	43	39	1.901	2.096	-22.48	-18.48
thermal	4.78	16	7	1.464	3.347	-11.22	-2.22
steering	9.2	11	10	1.087	1.196	-1.8	-0.8
TOTAL	**116.57**	**420**	**244**	**2.09**	**3.603**	**-303.43**	**-127.43**

On Earth, the subsystems that contributed the most variation from the Moon design are the chassis, propulsion, power and thermal. The Earth gravity will greatly increase the chassis mass and the Earth terrain and soil parameters will affect the drive system, wheel sizing and suspension. The temperature differences will also lead to varying power and thermal subsystem masses.

The Mars design differs from the Moon design in terms of chassis structure, propulsion, and power design. These subsystems will be affected by Mars' gravity, terrain characteristics and temperature ranges.

In most of these subsystems, the bounding design will be for Earth. The Mars and Moon UPV designs are similar in many aspects. The major difference between these two designs is the mass of the wheels. The wheel mass for Mars is approximately 5.6 times that of the Moon UPV. Nevertheless, the Earth design is much more massive then either one of the other designs. The Earth UPV is 3.6 and 1.875 times as massive as the Moon and Mars design, respectively. The variation in chassis mass is a significant contribution of the total mass differences. This limits the feasibility of designing a common system for all three planet conditions. Designing the UPV for the Moon and Mars, while customizing existing ATVs for Earth operations, is recommended.

Subsystem overview

One has to look at both the mass multiplier and percentage of the total system mass incurred by the subsystem to understand how much of an affect the subsystem design has on the overall vehicle. For example, the guidance system on Mars can be three times more massive then the guidance system on Earth. However, the mass of the guidance system does not contribute significantly to the mass over the overall system. As a result, the guidance system would not be considered a major consideration for commonality between the different designs. The figure below highlights the subsystems that will have a large impact on the level of commonality that can be achieved between the different operating environments. This is based on the commonality results from PSV and an understanding of how the subsystem operates. The baseline design will be for the Moon. The blue boxes highlight the systems that will vary from the baseline design only on Earth. The yellow boxes highlight the systems that will vary from the baseline design only on Mars. The green boxes highlight the systems that will different significantly in both environments.

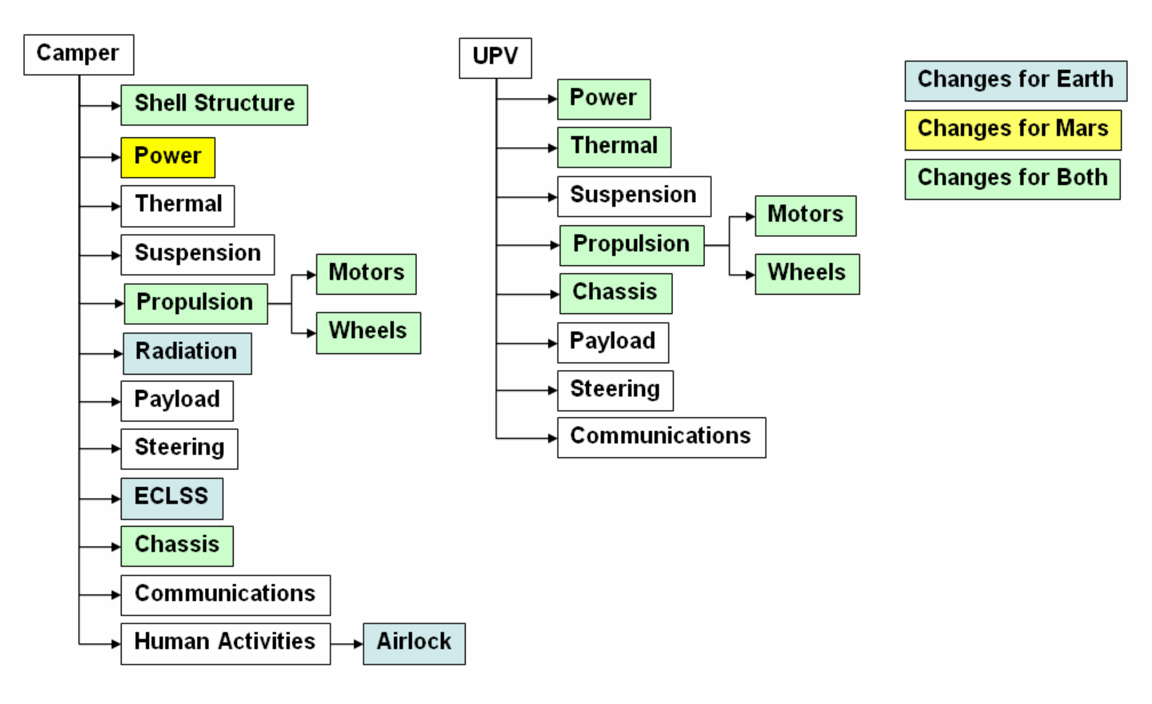


Figure 53: Subsystem changes, graphical overview

The following diagram is a pictorial presentation of these subsystems. This diagram does not show all of the subsystems that will vary because of display limitations. The colors correspond to the key provided in the figure above.

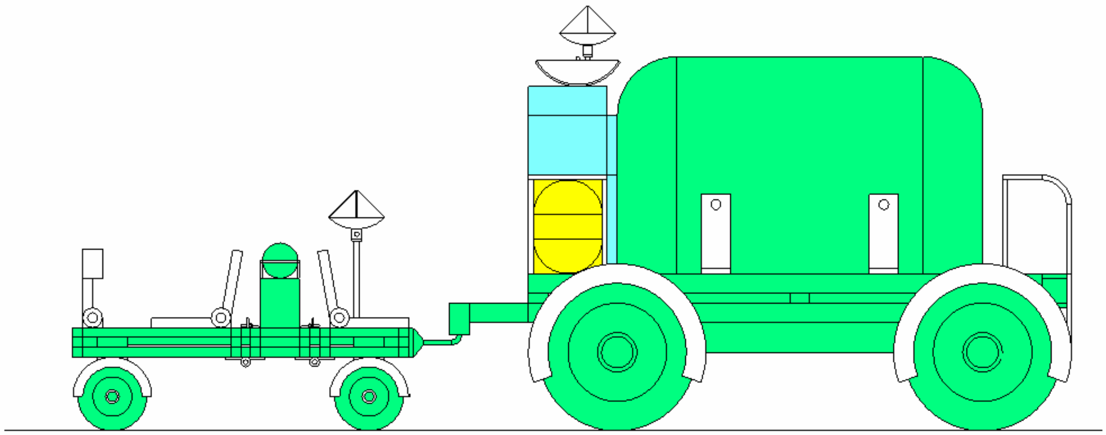


Figure 54: Subsystem changes, drawing

Two design options

There are two design options that can be taken when designing for the camper and the UPV: fix the chassis frame for all environments or design customized chasses. The chassis subsystem was chosen because it acts as the connecting station for many of the other subsystems. As a result, the geometry of the chassis will greatly impact how the other subsystems are designed and interface with each other. The universal chassis frame can help with modularization. However, there is a mass overhead will incur when operating the vehicle in an environment it was not optimized for. On the other hand, customized chasses for different environments will result in more locally optimized designs but will require a large amount of development cost.

Conclusion

The fix chassis geometry is recommended for several reasons. A common chassis designed for different environments will reduce multiple chassis design costs. This will also increase the number of common components between the different vehicle designs. A universal chassis design will also reduce the supply chain complexities and logistics with manufacturing and upkeeping these vehicles. Furthermore, this will make subsystem modules interchangeable for different missions and environments. For example, a pressurized water tank can be easily interfaced with both the campers on Earth and the Moon. In addition, the chassis beam profiles can vary to account for different loads. This will reduce excess mass while maintaining the geometry of the chassis. Nevertheless, the crew station and propulsion systems (especially the wheel dimensions) still need to be significantly modified based on terrain and the external environment.

Furthermore, the UPV is recommended to be designed for operations on the Moon and Mars. Designing a UPV for all three environments will result in a vehicle with an extremely large overhead that will be difficult to transport to the Moon and Mars. It is recommended that existing ATVs can be customized for Earth operations. Furthermore, over designing the UPV chassis can be beneficial to DRM 3 and DRM 4 operations on the Moon.

6.2 DRM 3 and DRM 4 Revisited

The team had time at the end of the semester to briefly revisit the possibility of using the UPV for DRM 3 and DRM 4 operations. There was enough time to perform a structural analysis of the chassis. The maximum horizontal forces and vertical loads at the end of the chassis are determined to be enough for limited DRM 3 and DRM 4 operations.

The initial purpose of DRM 3 and DRM 4 was for resupply and infrastructure buildup at the base. Resupply in DRM 3 consisted of moving cargo from the lander to the base within three km. This can involve some form of lifting mechanisms or towing capacities. DRM 4 includes the infrastructure buildup within three km of the base. Operation possibilities include moving regolith, deploying small equipments around the base, light surface construction, and connecting base modules with wires, etc.

The results from TVM show that the chassis structure is capable of withstanding a horizontal force of approximately $6\text{x}10^6$ N and a vertical point force at the front of the chassis of approximately 2,296 N. An average regolith density of 1,250 kg/m^3 and the bucket capacity of SOLAR 010 and 015 Plus vehicles (the table below shows the specifications for SOLAR Mini Excavators) are used to determine a bucket capacity of 0.04 m^3 and a lifting capacity of approximately 1,408 kg on the moon. A plowing force of $6\text{x}10^6$ N can also be applied horizontally to the chassis before the maximum allowable deflection is reached. For these operations, interfaces must be designed into the chassis that allow for attachment arms, blades, etc. Future work will be to determine the stress concentrations around these interfaces for different type of appendages.

Model	**Operating Weight (kg)**	**Bucket Capacity (cbm)**	**Engine Power (PS/rpm)**	**Digging Force (tons)**
SOLAR 010	770	0.023	9.5/2250	0.82
SOLAR 015 Plus	1540 / 1570	0.04	17.2/2300	1.27
SOLAR 030 Plus	2740 / 2840	0.069	24.5/1950	1.85
SOLAR 035	3140 / 3240	0.1	24.5/1950	2.28
SOLAR 055-V Plus	5500	0.13 ~ 0.17	51.8/2200	3.7

Table 29: DRM 4 tools

Although the chassis structure allows for resupply and infrastructure buildup, the extent of such operations will be largely constraint by the propulsion subsystem. The power need by the propulsion subsystem for DRM 3 and DRM 4 operations will impact the volume, mass and energy consumption of the system. Future works will be to analyze the propulsion capabilities of the UPV for resupply and infrastructure buildup.

Reference
DAEWOO Mini Excavator, http://www.allproducts.com/singapore/celtractors/Product-20048515149.html May 5, 2006.

7. Summary and Conclusions

7.1 Discussion

The value delivering activities on the surface were captured in the four types of design reference missions (DRM). These missions are representative of major exploration surface activities. DRM 1 incorporates science explorations within a 20 km radius of the base. DRM 1 will be performed on one EVA and have a total range of 60 km. DRM 2s are long traverses totaling up to 100 km on the Moon and 200 km for Mars and Earth. The duration for a DRM 2 ranges between 5 and 10 days. The total range of travel is expected to be 300 to 600 km. DRM 3 is the resupply of the base with cargo located up to 2 km away. Finally, DRM 4 is the build and maintenance of infrastructure at the base or outpost.

In addition, this project independently confirmed the superiority of the camper architecture. The camper architecture eliminates the duplicate functionality of a pressurized rover and unpressurized rover system. The selected architect also enhances the flexibility of the total system in terms of functional options.

Furthermore, a Terrain Vehicle Model (TVM) was created that included a set of subsystem models with more resolution compared to the PSV. The TVM relied mostly on physics-based and engineering-based models. The individual subsystems are much more defined in terms of inputs, outputs, and interfaces. Furthermore, TVM includes modules that were not considered by PSV, such as the radiation subsystem. More options and design variables were built into the TVM. For example, there is a wider range of structural materials available for selection.

The team also created a versatile integrated capability modeling framework for surface operations based on vehicle designs. The Mission Utility Simulation Environment (MUSE) serves as a validation tool of the vehicle capabilities. MUSE allows for iterative designs by incorporating the actual terrain data and vehicle design with what the astronauts will actually be doing on the Moon. MUSE also identifies power modularity opportunities and can be extended to monitoring other consumables.

Design specifications were generated for an extensible planetary surface mobility system. The design passed through the vehicle design iteration once and twice in MUSE. Specific dimensions and power usages of the different subsystems are provided for both the camper and the UPV. The dedicated UPV and camper were design with a common core and extensible modules for Earth/Moon/Mars environment customizations. In addition, computer aided drawings were produced of the UPV and the camper.

7.2 Future Work

8. Acknowledgements

The 16.89/ESD 352 Team would like to extend acknowledgements to the following people for all their help, support, guidance and insights that made this project successful:

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Rich Volpe – JPL
Rick Welch – JPL
Brian Wilcox – JPL
Paul Wooster – MIT Aeronautics and Astronautics

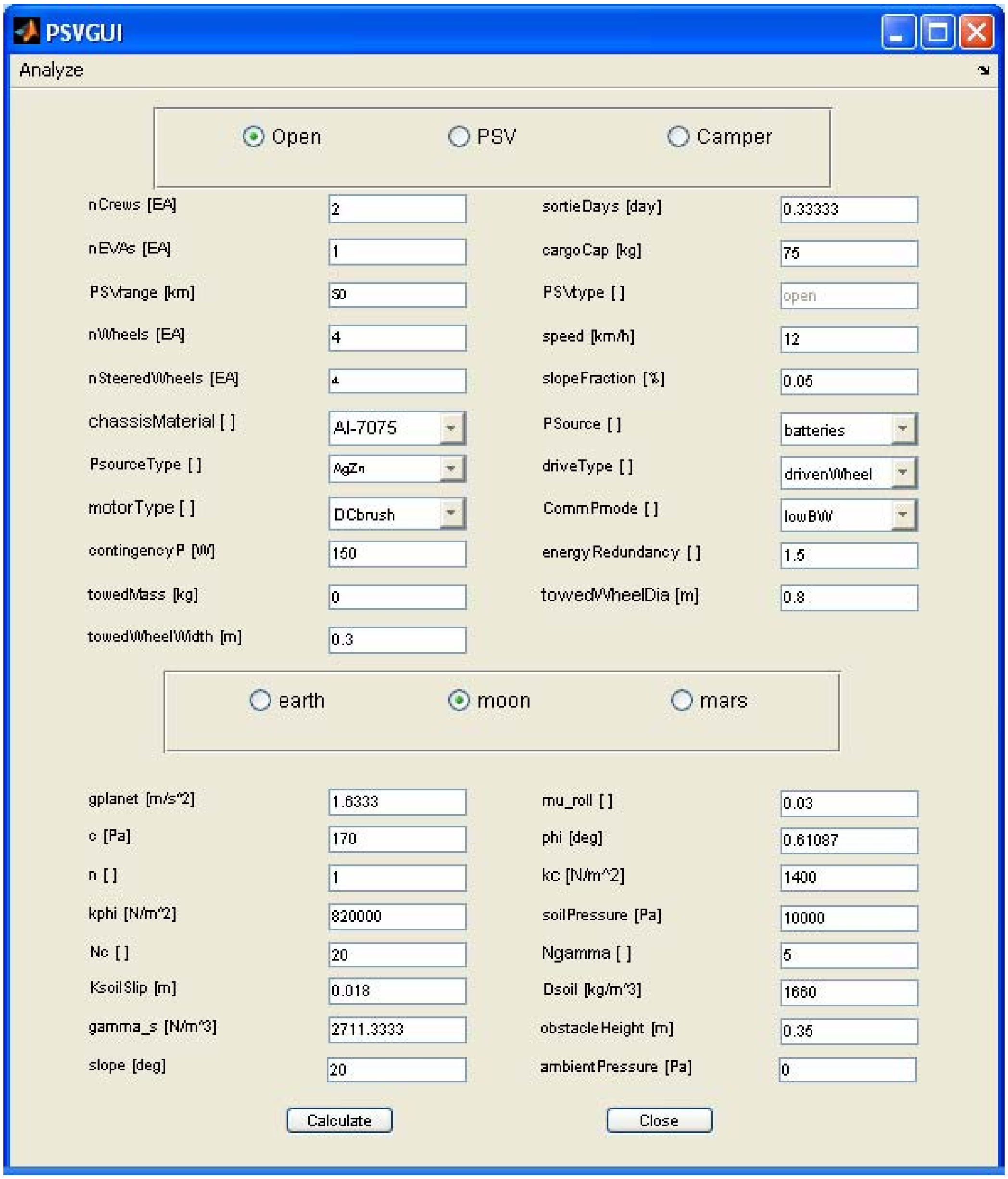
9. References

Appendices

Appendix to Section 3.3, Architecture Analysis

DRM-1 Mass analysis

In order to perform the architecture analysis, the PSV code originally written by Afreen Siddiqi and updated by Seungbum Hong was implemented. The Matlab scripts for this code are available elsewhere in the appendix. The section that follows is simply meant to explain what inputs were chosen for the code, and how the outputs were determined. Figure 55: PSV GUI is the GUI (Guided User Interface) for running the PSV code.



● Open ○ PSV ○ Camper

nCrews [EA]	2	sortieDays [day]	0.33333
nEVAs [EA]	1	cargoCap [kg]	75
PSVrange [km]	50	PSVtype [ ]	open
nWheels [EA]	4	speed [km/h]	12
nSteeredWheels [EA]	4	slopeFraction [%]	0.05
chassisMaterial [ ]	Al-7075	PSource [ ]	batteries
PsourceType [ ]	AgZn	driveType [ ]	drivenWheel
motorType [ ]	DCbrush	CommPmode [ ]	lowBW
contingencyP [W]	150	energyRedundancy [ ]	1.5
towedMass [kg]	0	towedWheelDia [m]	0.8
towedWheelWidth [m]	0.3		

○ earth ● moon ○ mars

gplanet [m/s^2]	1.6333	mu_roll [ ]	0.03
c [Pa]	170	phi [deg]	0.61087
n [ ]	1	kc [N/m^2]	1400
kphi [N/m^2]	820000	soilPressure [Pa]	10000
Nc [ ]	20	Ngamma [ ]	5
KsoilSlip [m]	0.018	Dsoil [kg/m^3]	1660
gamma_s [N/m^3]	2711.3333	obstacleHeight [m]	0.35
slope [deg]	20	ambientPressure [Pa]	0

Figure 55: PSV GUI

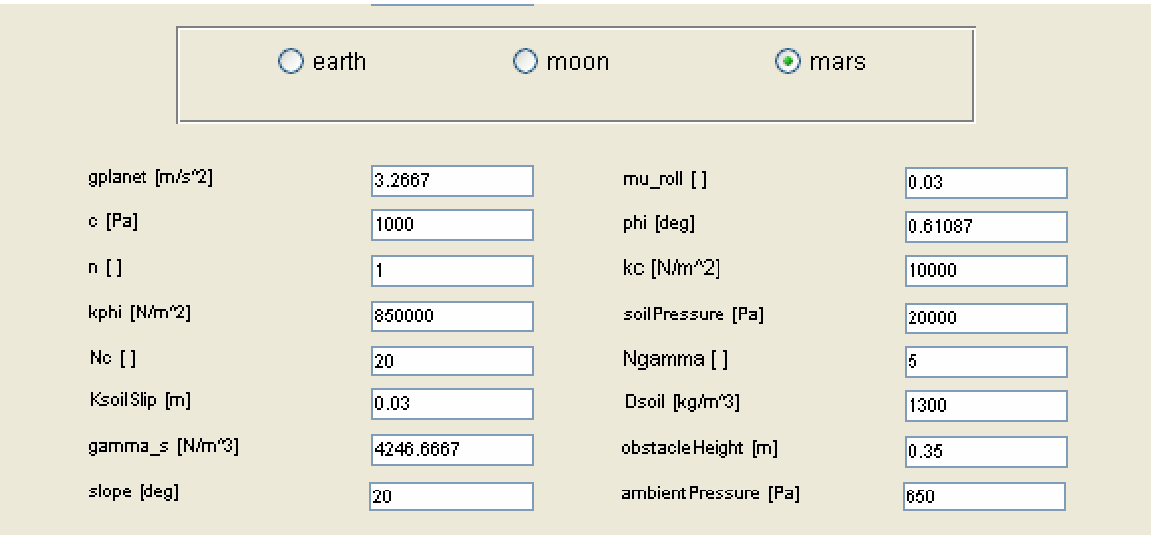
DRM–1 Inputs

For DRM-1 sorties on both the Moon and Mars, the following values, or ranges of values, were input as seen in Table 30: DRM-1 inputs:

Table 30: DRM-1 inputs

Variable name	Value	Description
nCrews	1, 2, 3	Number of crew per vehicle
sortieDays	0.3333	8 hour EVA duration
nEVAs	n/a	As the crew already is on an EVA, this value is irrelevant for DRM-1 calculations
cargoCap	200*n_{crew} kg	The vehicle is sized to hold the entire crew from another vehicle in case of emergency. A suited astronaut is assumed to have a mass of 200 kg
PSVrange	60 km	Total distance driven
PSVtype	open	Unpressurized vehicle option
nWheels	4	
speed	10-20 km/hr	Maximum vehicle speed, set based on Apollo experiences
nSteeredWheels	4	Number of powered wheels
slopeFraction	0.05	Amount of driving time that the vehicle drives over worst-case scenario slope
chassisMaterial	Al 7075	
Psource	Batteries, solar, fuel cells, isotope	Type of power system used
PSourceType	Ag-Zn, Si	Type of power material: is Ag-Zn for batteries; Si for solar, otherwise is unneeded
driveType	drivenWheel	
motorType	DC brush	
commPmode	Low BW	
contingencyP	150 W	Extra power for emergency uses
energyRedundancy	1.5	
towedMass	0	Mass the vehicle is towing
towedWheelWidth	n/a	
TowedWheelDia	n/a	

The lunar sortie soil data was input as displayed above in the GUI figure. The values were obtained from a variety of sources, as outlined elsewhere in this design document. The Mars data is seen below, in Figure 56: Mars Data in PSV GUI:



○ earth ○ moon ● mars

gplanet [m/s^2]	3.2667	mu_roll [ ]	0.03
c [Pa]	1000	phi [deg]	0.61087
n [ ]	1	kc [N/m^2]	10000
kphi [N/m^2]	850000	soilPressure [Pa]	20000
Nc [ ]	20	Ngamma [ ]	5
KsoilSlip [m]	0.03	Dsoil [kg/m^3]	1300
gamma_s [N/m^3]	4246.6667	obstacleHeight [m]	0.35
slope [deg]	20	ambientPressure [Pa]	650

Figure 56: Mars Data in PSV GUI

Once the each of the inputs was run, the data was output to an Excel spreadsheet.

The PSV outputs a number of values, including the wheel width and wheel diameter, both of which will be used for the DRM-2 analysis. However, the critical outputs of the PSV code for the purposes of the DRM-1 architecture analysis are the total vehicle mass and the power mass.

In order to determine the total system mobility wet mass, a series of assumptions were made regarding a variety of parameters. Those values are listed in Table 31: DRM-1 constants below:

Table 31: DRM-1 constants

Variable	Value	Description/Comments
days surface duration [d]	5	Lunar sortie is nominally 7 days, no exploration is conducted on first or last day
walking speed [km/h]	3	Based on Apollo data [Apollo Lunar Surface Journals]
walking range [km]	21	
time per site [ch]	2	Based on Apollo data [Apollo Lunar Surface Journals]
driving range [km]	60	Exceeds Apollo standards
range/site [km]	3	Considered a reasonable distance between science sites of interest [Apollo Lunar Surface Journals]
total suit time [h]	8	Based on considerable spacesuit legacy
loading/unloading time [ch]	2	

Given this information, the mass of the additional cart carried by any astronauts who are walking can be determined:

$$m_{cart} = \frac{50 \times t_{sci}}{2} \qquad (1)$$

where, m_{cart} = mass of cart, kg

t_{sci} = science time of walking astronauts, hr

The mass becomes heavier with the more science time, because it must be redesigned to carry the additional samples. However, to conduct this analysis first the science time of the walking astronauts must be calculated, using the following formula**:**

$$t_{sci} = n_{crew} \times (t_{EVA} - \frac{r_{walk}}{v_{walk}}) \qquad (2)$$

where,
n_{crew} = number of crew walking
t_{EVA} = time on EVA (total suit time), hr
r_{walk}= walking range, km
v_{walk} = walking speed, km/hr

Now the total system mobility wet mass can be solved for:

$$m_{sys} = n_{veh} \times m_{veh} + m_{cart} + n_{days} \times m_{pow} \times 1.5 \qquad (3)$$

where,
m_{sys} = total system mobility wet mass, kg
n_{veh} = number of vehicles
n_{days} = number of days of exploration
m_{pow} = power mass, kg

The 1.5 represents the additional structure to be towed by the vehicle to hold the fuel. Now that the mass has been determined, the cumulative number of sites must be calculated.

DRM-1 number of sites

First, the number of science sites visited by the astronauts walking is computed, as seen in the following formula:

$$n_{sites,w} = \frac{t_{sci}}{t_{site}} \qquad (4)$$

where,
$n_{sites,w}$ = number of sites visited walking
t_{site} = time per site, crew-hr

To determine the number of sites visited by the crew driving, the same equation is used. Here, however, t_{sci} is computed differently than before:

$$t_{sci,d} = n_{crew} \times (t_{EVA} - t_{load} - t_{unload} - t_{drive}) \qquad (5)$$

where,
t_{load} = time taken to load the vehicle, hr
t_{unload} = time taken to unload the vehicle, hr
t_{drive} = driving time, hr

However, the three quantities outlined above (t_{load}, t_{unload}, t_{drive}) need to be found before this equation can be used. The loading and unloading times are found via a simple calculation, defined by:

$$t_{load} = \frac{tc_{load} \times n_{veh}}{n_{crew}} \qquad (6)$$

where, tc_{load}= total crew hour time to load a vehicle, crew-hours

Since, $tc_{load} = tc_{unload}$, the calculation for t_{unload} is exactly the same as equation 6.

The equation used to determine t_{drive} is quite simple as well:

$$t_{drive} = \frac{r_{veh}}{v_{veh}} \qquad (7)$$

where, r_{veh} = range of the vehicle
v_{veh} = speed of the vehicle

For the initial analysis, the limiting factor is always the time spent driving, as it is assumed that the entire range is covered on every traverse.

The cumulative number of sites visited is:

$$n_{sites,tot} = n_{days} \times (n_{sites,w} + n_{sites,d}) \qquad (8)$$

where, $n_{sites,tot}$ = total number of sites visited
$n_{sites,d}$ = number of sites visited driving

With each architecture and each independent variable considered, the total trade space can then be displayed and analyzed. The first figure presented is that of the Lunar DRM-1 entire trade space.

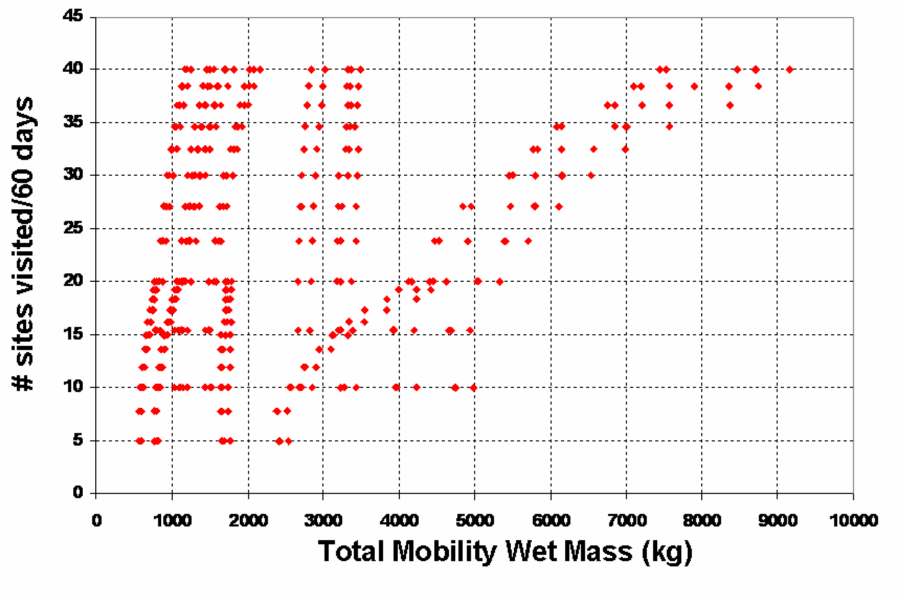


Figure 57: Lunar DRM-1 Trade Space

The significantly heavier designs are those powered by radio-isotopes. The other 3 groups are solar power, fuel cells, and batteries. The solar panels were the lightest design, but the necessary surface area was prohibitively large. Additionally, there was significant concern about their ability to operate in craters or during the lunar night. Therefore, fuel cells were chosen as the ideal option. For further analysis see Section 3.3, where this issue is discussed in greater depth. Following the Lunar trade space is that of the Mars DRM-1 trade space.

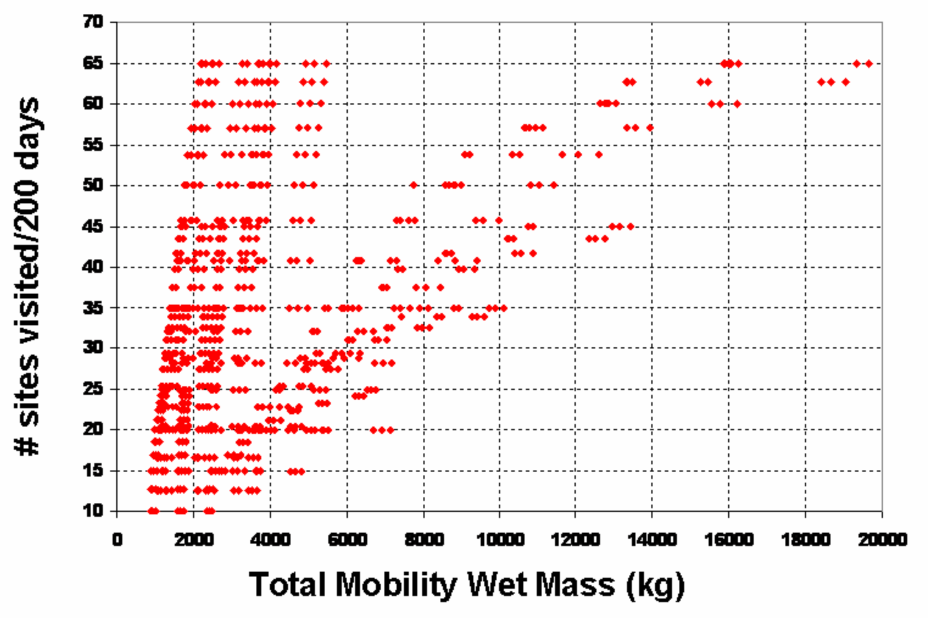


Figure 58: Mars DRM-1 trade space

The same variations between radio-isotopes, solar cells, fuel cells and batteries hold here as for the lunar DRM-1 analysis. This graph does not much in the way of detailed comparisons between the other architecture options. That information is much easier gleaned from the following figure, the Mars DRM-1 Pareto front.

Additionally, from the trade spaces it was found that given the mass requirements for a mission to either Moon or Mars, that all crew members could be mobilized. This situation could be critical if a landing vehicle failed to touch down near the habitation module, so that the crew had to travel greater than a nominal walking distance.

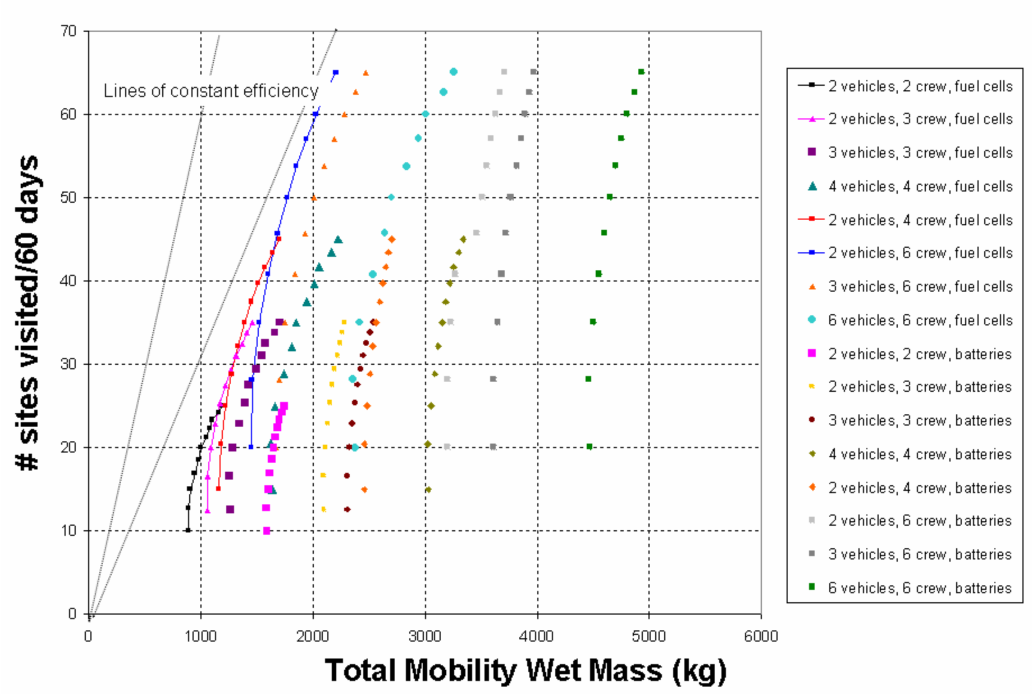


Figure 59: Mars DRM-1 Pareto Front

DRM-2 Mass analysis

For the DRM-2 analysis, both the mass of the open unpressurized vehicles and the pressurized vehicles (either pressurized rovers or campers) must be computed. First, the method for determining the total system mobility wet mass if the pressurized rover will be explained.

Pressurized Rover

The initial steps taken are the same as those listed above for the DRM-1 mass estimates, with two exceptions, the first being the speed is held constant at 20 km/hr and the second being that the calculation of total mass is not computed (Equation

$$m_{sys} = n_{veh} \times m_{veh} + m_{cart} + n_{days} \times m_{pow} \times 1.5 \qquad (3)).$$

This step will not be completed until the pressurized rover mass has been found. Once again, the PSV code is utilized with the following inputs:

Table 32: Pressurized Rover DRM-2 inputs

Variable name	Value	Description
nCrews	2, 3, 4, 6	Number of crew per vehicle
sortieDays	5-10	Total trip duration
nEVAs	nCrews* sortieDays	1 EVA per crew member per day
cargoCap	0	Payload mass is built into model
PSVrange	300 km (Moon) 600 km (Mars)	Total distance driven
PSVtype	PSV	Pressurized rover
nWheels	4	
speed	15 km/hr	Maximum vehicle speed, set based on Apollo

		experiences
nSteeredWheels	4	Number of powered wheels
slopeFraction	0.05	Amount of driving time that the vehicle drives over worst-case scenario slope
chassisMaterial	Al 7075	
Psource	Batteries, solar, fuel cells, isotope	Type of power system used
PSourceType	Ag-Zn, Si	Type of power material: is Ag-Zn for batteries; Si for solar, otherwise is unneeded
driveType	Driven wheel	
motorType	DC brush	
commPmode	Low BW	
contingencyP	150 W	Extra power for emergency uses
energyRedundancy	1.5	
towedMass	Defined below in Eq. 10	The rover is sized to tow additional fuel mass for the unpressurized vehicles, and any carts for astronauts walking on EVA
towedWheelWidth	UPV wheel width	
TowedWheelDia	UPV wheel diameter	

Once again, the critical outputs are the total vehicle mass and the power mass. The total mobility system wet mass (for the pressurized rover case) is then computed by the following equation:

$$m_{tot} = n_{veh,p} \times (m_{tow} + m_{veh,p}) + n_{veh,u} \times m_{veh,u} \tag{9}$$

where,
m_{tot}= total system mobility wet mass, kg
$n_{veh,p}$ = number of pressurized rovers
m_{tow}= towed mass, kg
$m_{veh,p}$ = mass of pressurized rover
$n_{veh,u}$ = number of unpressurized vehicles
$mv_{eh,u}$ = mass of unpressurized vehicles, kg

The towed mass does not include the vehicle itself, as that is assumed to be able to drive behind the pressurized rover. The towed mass is specified by:

$$m_{tow} = \frac{n_{veh,u} \times m_{pow,u} \times \left(\frac{r_{veh,p}}{r_{veh,u}} + d_{sci} - 1 \right) \times 1.5 + m_{cart}}{n_{veh,p}} \tag{10}$$

where,
$m_{pow,u}$ = power mass of upv, kg
$r_{veh,p}$ = range of pressurized rovers, km
$r_{veh,u}$ = range of unpressurized rovers, km
d_{sci} = science days

The ratio of the ranges sizes the additional power mass needed to drive the unpressurized vehicle autonomously over the long-distance traverse. The additional power masses can be specified by stating that an additional power mass is required for every day of exploration, and a factor of 1.5 was used for the additional structure needed to house this additional mass for towing purposes. The one accounts for the fact that one of the total power masses is already included in the vehicle design.

Camper

The analysis process for the camper uses many of the same steps as the pressurized rover. The differences will be outlined in this section.

For the camper, the initial code run is for the camper, not the unpressurized vehicles. The inputs are as specified below, with the only changes being the PSV type, the towed mass, the towed wheel width, and the towed wheel diameter, as the last 3 variables are set to 0 kg, 0 m, and 0m respectively.

Table 33: Pressurized Rover DRM-2 inputs

Variable name	Value	Description
nCrews	2, 3, 4, 6	Number of crew per vehicle
sortieDays	5-10	Total trip duration
nEVAs	nCrews* sortieDays	1 EVA per crew member per day
cargoCap	0	Payload mass is built into model
PSVrange	300 km (Moon) 600 km (Mars)	Total distance driven
PSVtype	camper	
nWheels	4	
speed	15 km/hr	Maximum vehicle speed, set based on Apollo experiences
nSteeredWheels	4	Number of powered wheels
slopeFraction	0.05	Amount of driving time that the vehicle drives over worst-case scenario slope
chassisMaterial	Al 7075	
Psource	Batteries, solar, fuel cells, isotope	Type of power system used
PSourceType	Ag-Zn, Si	Type of power material: is Ag-Zn for batteries; Si for solar, otherwise is unneeded
driveType	Driven wheel	
motorType	DC brush	
commPmode	Low BW	
contingencyP	150 W	Extra power for emergency uses
energyRedundancy	1.5	
towedMass	0	The camper is not towing another vehicle
towedWheelWidth	0	
TowedWheelDia	0	

With this given data, then the unpressurized vehicles are sized. The inputs to the upv that differ from those presented in Table 1 are presented in Table 5.

Table 34: DRM-1 inputs

Variable name	Value	Description
cargoCap	0	The vehicle is oversized already with its towing capacity, and is assumed to therefore be able to carry additional astronauts as part of the design.
speed	15 km/hr	Maximum vehicle speed, set based on Apollo experiences and the same as the camper speed
Psource	fuel cells	Previously found to be the best in the DRM-1 analysis
towedMass	m_{camp}	Mass the vehicle is towing

towedWheelWidth	wid_{camp}	Output from PSV model
TowedWheelDia	dia_{camp}	Output from PSV model
slope	10 degrees	Previously, this value was held at 20 degrees, but with the extra towed mass this number is unreasonable. The upv alone should be able to handle 20 degree slope without the additional mass quite easily.

Therefore, the total system mass is defined as:

$$m_{tot} = n_{veh,p} \times m_{veh,p} + n_{veh,u} \times m_{veh,u} + m_{add} \qquad (11)$$

where, m_{add} = additional power mass, kg

Since the upvs are only designed to transport the camper 60 km, there must be additional mass made to tow the vehicle over the rest of the long-distance traverse, as well as on the short explorations. The additional power mass is defined as:

$$m_{add} = \left(m_{pow,u} \times 2 \times d_{sci} + m_{pow,p} \times \frac{r_{veh,p}}{r_{veh,u}} \right) \times 1.5 + m_{cart} \qquad (12)$$

where, $m_{pow,u}$ = mass required to power the upv on exploration, kg
d_{sci} = science days
$m_{pow,p}$ = mass to tow the camper over its range, kg

The upv exploration power mass is sized by taking ¼ of the dry mass, which was the average of the ratio found between power mass and dry mass through a variety of trials. With no camper to tow, the power mass should decrease significantly. The 2 is in the equation because only 2 upvs are taken on an exploration traverse. The third is always left behind with the camper, since there is no need to waste the additional fuel.

DRM-2 Cumulative number of sites visited

This calculation is the same for both the pressurized rover and camper architectures. The first step is to calculate the number of sites visited on one day, as seen in Equations 4-8, with n_{days} equal to 1.

The total number of sites visited over a cumulative time period (60 days for the Moon, 200 days for Mars) is defined as:

$$n_{site,tot} = \left(d_{sci} + n_{sites,u} \times d_{sci} \right) \times \frac{t_{\exp}}{t_{sortie}} \qquad (13)$$

where, $n_{sites,tot}$ = cumulative number of sites
$n_{sites,u}$ = number of sites visited on exploration day
t_{exp} = cumulative time period for site exploration
t_{sortie} = length of sortie duration

It was assumed that each waypoint along the exploration path is a science site as well, which accounts for the first inclusion of science days in Eq.

$$n_{site,tot} = \left(d_{sci} + n_{sites,u} \times d_{sci} \right) \times \frac{t_{\exp}}{t_{sortie}} \qquad (13).$$

The determination of the number of science days given a speed and sortie duration is defined as:

$$d_{sci} = \left(t_{sortie} - \frac{r_{veh,p}}{v_{veh,p} \times t_{drive}} \right) \tag{14}$$

where, $v_{veh,p}$ = speed of pressurized vehicle, km/hr
t_{drive} = time spent driving, hr

The time spent driving is assumed to be 8 hours a day for the purposes of this analysis. Anything more would require an additional EVA or enhanced suit design. Also, more time spent driving would be extremely tiring for the astronauts, as navigation over rough terrain is both physically and mentally challenging.

With all the metrics now calculated, the trade space can be created, and the various options analyzed.

DRM-2 Trade Spaces

The following figures outline the entire trade space analyzed for each planetoid for the DRM-2 mission. The first figure presented is that of Lunar DRM-2 Trade space.

After ruling out the other power systems, due to a very brief analysis and given the data of the DRM-1 analysis, these graphs simply represent the array of architectures. There are obviously some outliers in terms of efficiency. These are 1 pressurized vehicle architecture, and the reason for not selecting them (along with a more detailed Pareto Front figure) is in the body of this report.

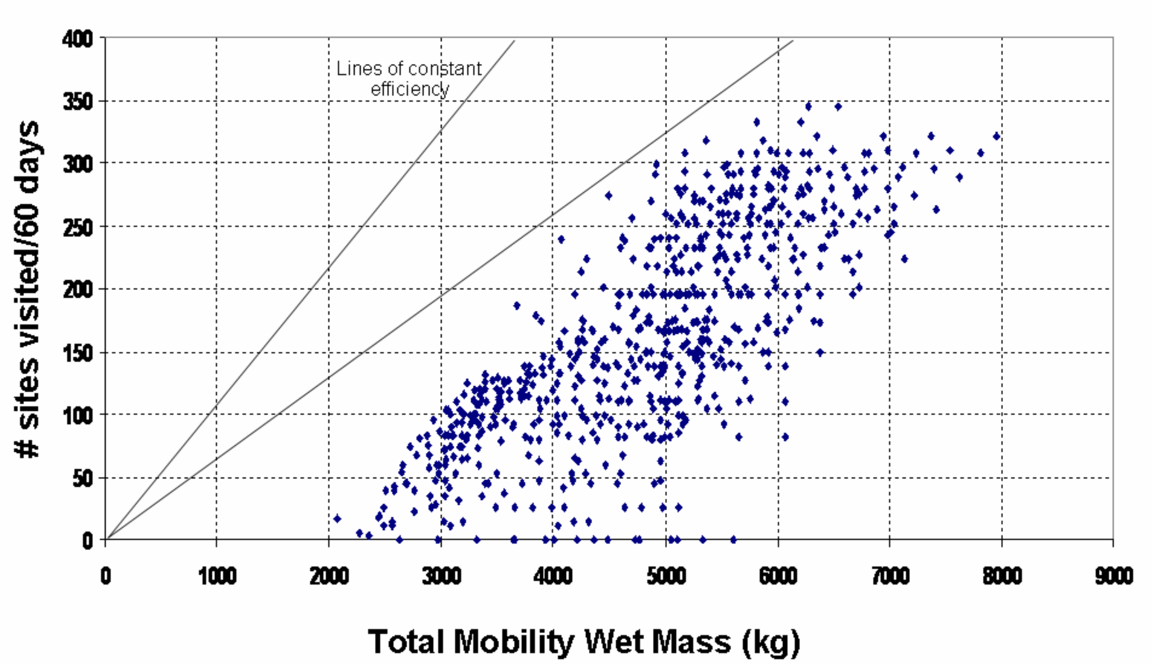


Figure 60 Lunar DRM-2 Trade Space

The same level of analysis was undertaken for the Mars DRM-2. The following figure is the complete trade space.

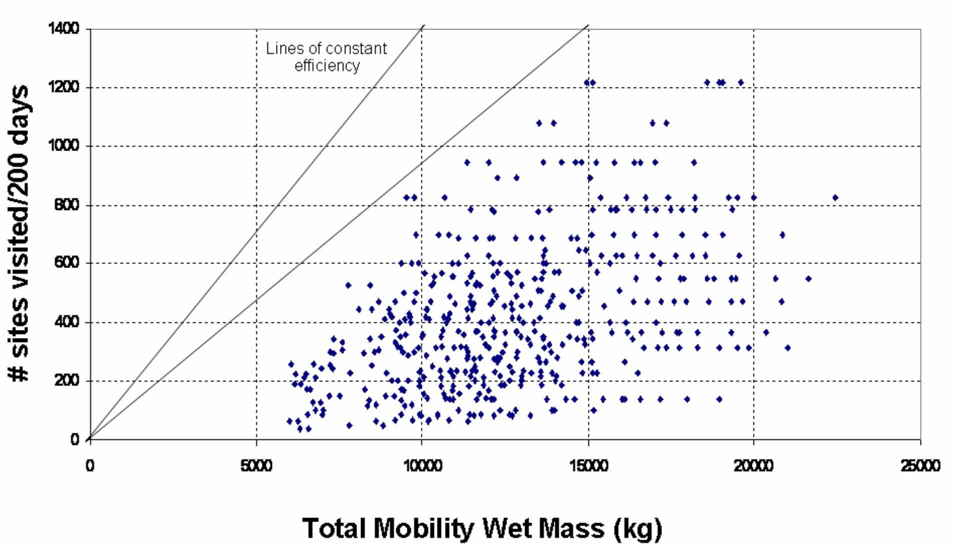


Figure 61 Mars DRM-2 Trade Space

Similar to the Moon DRM-2 analysis, only fuel cells architectures are included. Here the most efficient outliers are the 6 person architectures, especially with only 2 or 3 vehicles. The following figure, the pareto front for the Mars DRM-2 architecture, provides a better visualization of this fact.

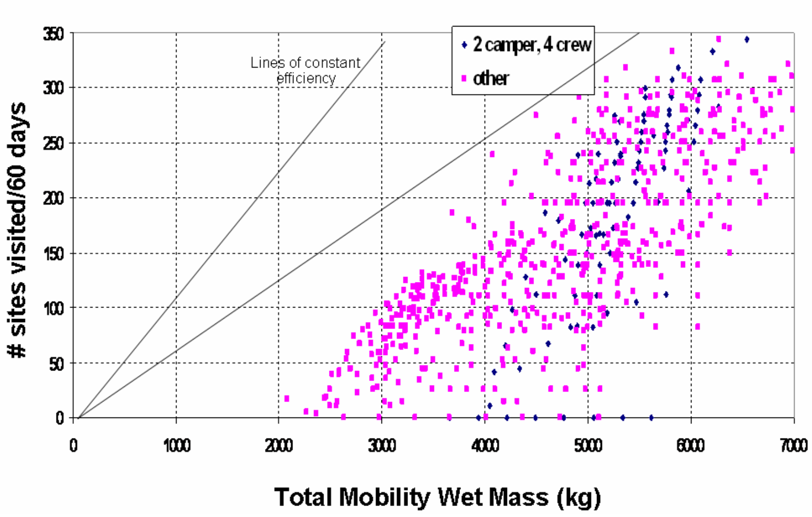


Figure 62 Mars DRM-2 Trade Space Pareto Front

In the graph, the 2 camper, 4 crew (2 crew each) is not the most efficient design. However, the better designs all use 6 crew members, and are not extensible. The cost to design one vehicle, as opposed to many vehicles optimized for each planetoid, is much less and justifies choosing a non-optimal solution for Mars.

References:

1. Apollo Surface Journal

Appendix to Section 3.4, Sensitivity Analysis

This Appendix displays all the additional figures and comments on the sensitivity analysis.

DRM-1 Sensitivity

In addition to the speed study mentioned in the body, an analysis of the range was done as well, as seen in Figure 63: Lunar Range DRM-1

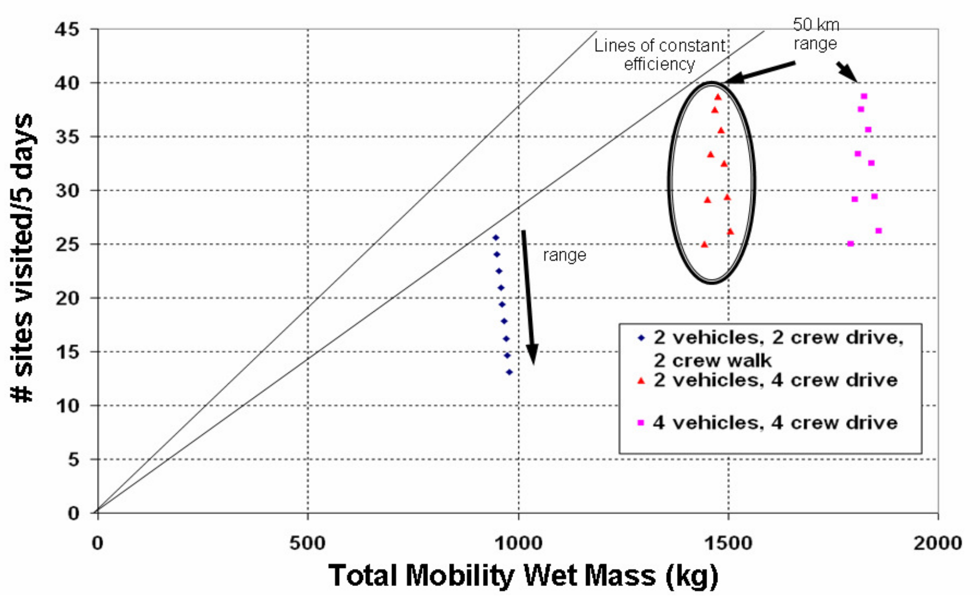


Figure 63: Lunar Range DRM-1

The max point for the efficiency in the case of the range values is 50 km, but this actually lends credence to the use of 60 km as the chosen range. The vehicle should be designed above some minimal constraints, so that after each EVA the astronauts are not returning merely on empty. With the vehicle able to travel a greater distance, it provides a reasonable margin of safety. Additionally, these numbers are based on certain assumptions (such as the 3 km range between sites) that would affect the overall numbers somewhat, but not the variation between each range option. Also, while the greater crew numbers may not be quite as efficient, the larger number of sites makes this a better option. This truth will become even more self-evident when connected with the DRM-2 analysis. Without the vehicles, the number of sites visited will drop tremendously. Making a decision on a lunar sortie mission (DRM-1) without analyzing the effects on a longer stay mission would be short-sighted and hurt the ability to produce an extensible architecture.

In most point designs, the limiting factor is the driving time. However, as the range decreases, the number of science sites becomes the main driver for the amount of science to be accomplished. A slight change was made to the architectural analysis procedure outlined elsewhere in the Appendix in order to account for this change.

No Mars DRM-1 sensitivity analysis was undertaken because it would have been redundant.

DRM-2

The Lunar and Mars DRM-2 sortie days are seen in the body of the report. This section outlines the other two variables explored: range and speed. Figure 64: Lunar DRM-2 Range displays the range data.

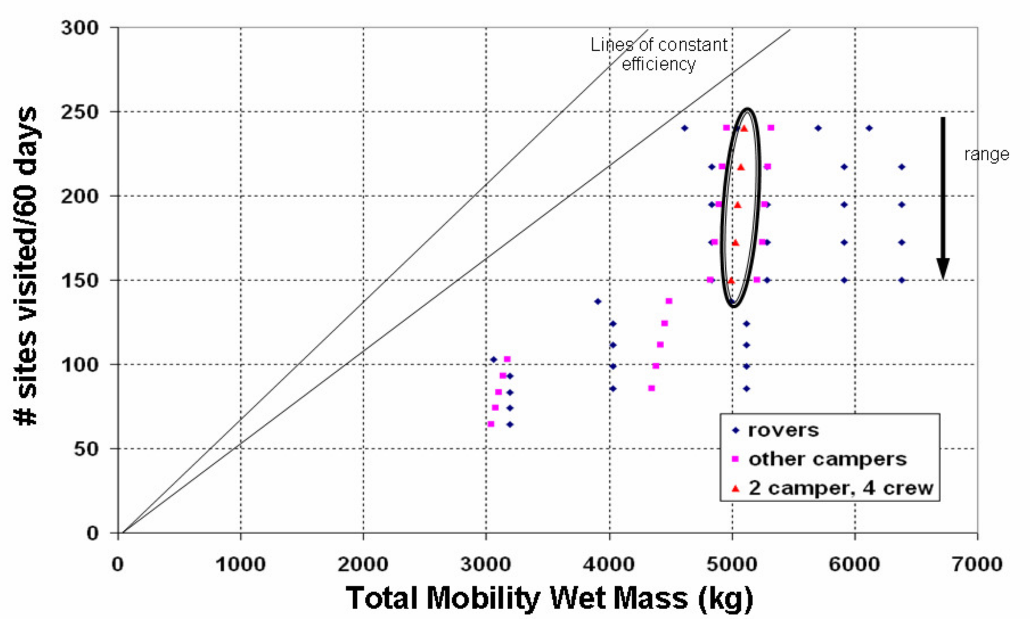


Figure 64: Lunar DRM-2 Range

This graph reveals one oddity of the analysis. Since the metric on the y-axis is based purely on the number of sites visited, rather than weighting sites by their distance from the base, the most number of sites are visited by the smallest range. This situation occurs because the driving time is minimized, leaving additional time for science. However, this may not be the most accurate analysis, but given the time and scope it was felt to be a reasonable approximation for metric analysis. It is important to notice that range is not a major mass driver; rather the vehicles are sized based on speed and duration, which will be seen in subsequent graphs, such as Figure 65: Lunar DRM-2 speed.

In this graph, once again the 2 camper, 4 crew (2 crew per camper) is dominated by the 1 vehicle architectures. However, as discussed previously elsewhere, the extra camper for exploration redundancy is worth the mass penalty. Additionally, the efficiency of the vehicle stops increasing around 12 km/hr, similar to the upv. However, more sites can be visited with the additional mass caused by the increase in speed. This trade-off should be made at the vehicle design level .

Overall, the lunar sensitivity analysis shows no reason for a change in the baseline design.

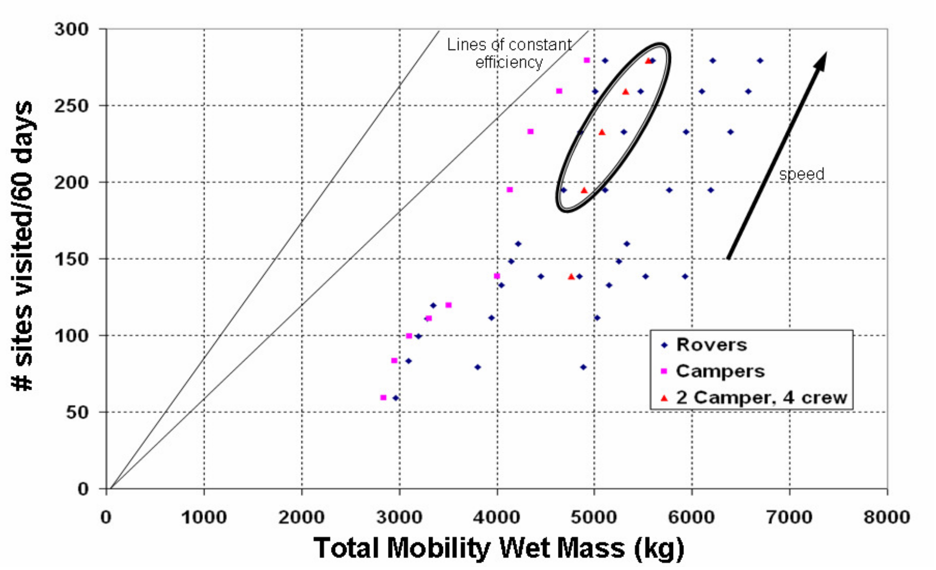


Figure 65: Lunar DRM-2 speed

The Mars sensitivity analysis is the final step that must be undertaken to verify the architecture decision, at least at this level of fidelity. Figure 66 Mars DRM-2 Speed represents the speed analysis.

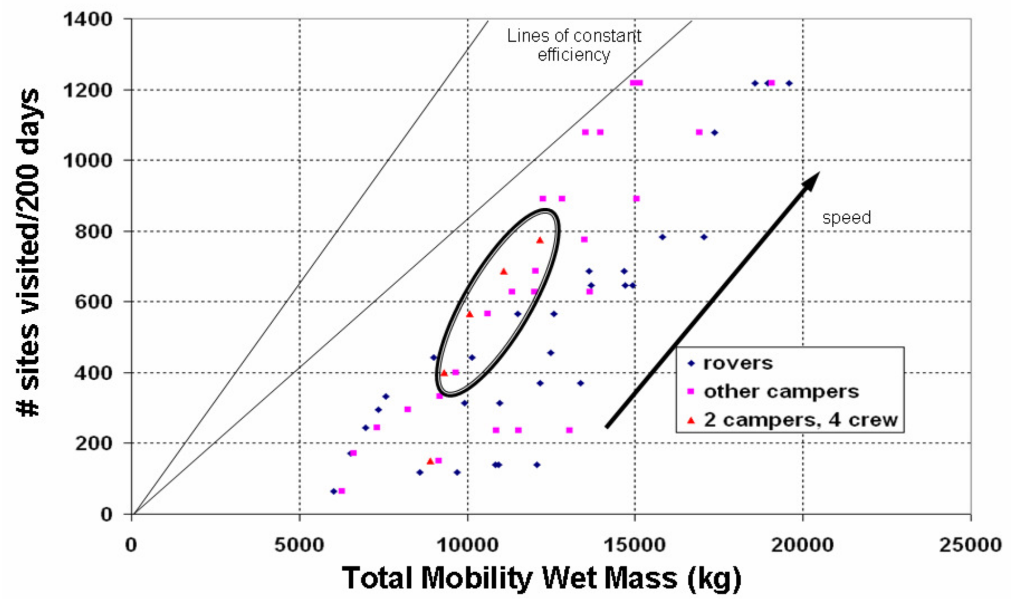


Figure 66 Mars DRM-2 Speed

In this graph, the baseline architecture is along the pareto front again. Like the lunar sensitivity analysis, there is not much increase in efficiency above 12 km/hr. As mentioned in the body of this report, the designs that allow for more sites to be visited all have all 6 crew on exploration. For reasons of extensibility, the baseline is kept to only hold 4 crew. This decision should also be remember when interpreting Figure 67 Mars DRM-2 Range.

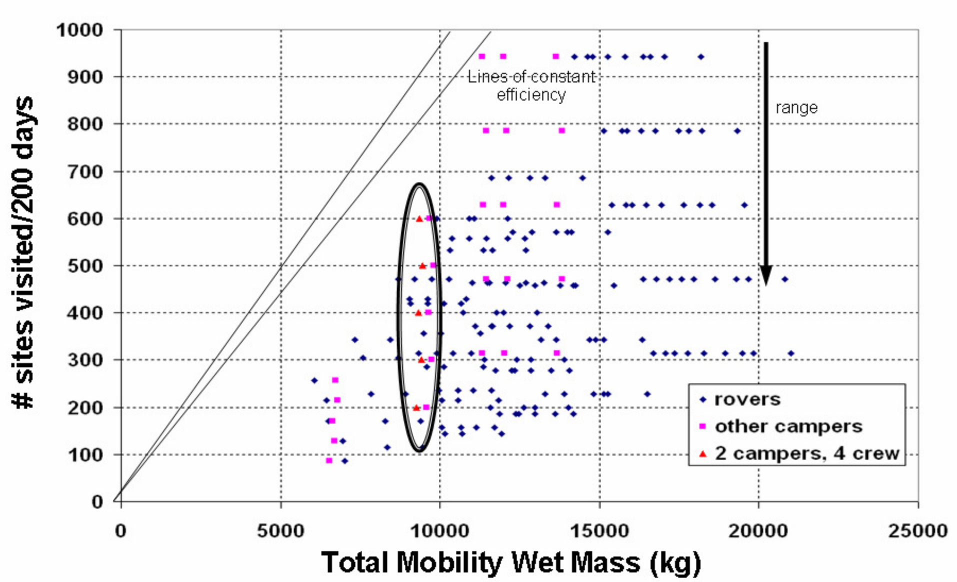


Figure 67 Mars DRM-2 Range

As mentioned in the lunar DRM-2 analysis, this graph shows one of the weaknesses of the number of sites metric as calculated here. The baseline architecture here does not do as well as in the other sensitivity analyses, but given the overall strengths, and the lack of realistic operational assumptions built into this analysis, there is not enough data to overturn the baseline selection.

In summary, the baseline selection was confirmed through the sensitivity analysis as described above.

Appendix to Section 3.5, Communication and Navigation

Communications Requirements

The following discussion provides a brief overview of the primary and secondary requirements for the communications system for the planetary surface mobility system. The primary requirements are broken down by whether a function must happen ("hard" requirement), or should happen ("soft" requirement).

Primary Hard Requirements

- *Must transport data from a mobile asset back to Earth at some point.* This requirement ensures that scientific data, one of the primary value-delivering processes in the system, is retrieved.
- *Must have continuous communications between the base and mobile asset regardless of line-of-sight.* This requirement is primarily for safety reasons, though the rationale varies depending on location:
    - Mars: The orbit and rotation of Mars, for example, makes continuous communications back to Earth difficult at best. It is assumed in the vehicle design study that there are always 2 astronauts at the base, so continuous communications between the base and the mobile asset must happen.
    - Moon: On the moon, it is assumed that the astronauts would either be at the base or on a sortie together. For landing sites on the near-side, the base should always have direct line-of-sight with Earth, though the mobile asset may not given the conditions of the local terrain. For landing sites on the far-side, neither the base nor the mobile asset will have direct line-of-sight with Earth, implying the need for at least a single space asset. Again, it is possible for the base to have direct line-of-sight with the space asset but not the mobile.

Primary Soft Requirements

6. *Should transport data from mobile to Earth continuously.* It is highly desirable for basic voice and telemetry communications and scientific data to be transported from the mobile asset to Earth continously "real-time". However, due to orbital and terrain considerations, this is not always possible without significant infrastructure deployment.
7. *Should be extensible across missions.* This requirement is intended to meet the extensibility goal of the project, though it should not drive the communications design.
8. *Should be cost-effective*. Space-based communications systems are historically very expensive. Thus, it is greatly desirable to ensure that the amount of use the system sees per dollar spent on the system is as high as possible.

There are also several high-level secondary requirements, or other aspects of the system that must be accounted for in the overall design. These requirements are self-explanatory.

Secondary Requirements

7. *Communication transmissions should be secure.*
8. *Tracking and navigation capabilities should not spectrally interfere with communicating elements.*
9. *The communication infrastructure should support mission elements for the duration of the mission lifetime.*
10. *Communicating elements should have the ability to survive and operate in abrasive, dusty environments with extreme radiation and thermal conditions.*
11. *Should be flexible and evolvable to meet the growing and changing demands of missions over time.*

Navigation System Requirements

The navigation system (also known as the Guidance, Navigation and Control – GN&C – system) is responsible for determining current and future position and direction and making the course corrections to get there. The GN&C system for the planetary surface mobility system has the following requirements:

1. *The planetary surface mobility system must be able to navigate from base to target(s) and back to base.*
2. *The GN&C system must identify the current location of a mobile asset with sufficient location accuracy to meet the requirements of the interfacing systems.*
3. *The GN&C system must predict the future location of a mobile asset assuming no course adjustments are made.*
4. *The GN&C system should receive accurate real-time position, velocity, acceleration, timing, and heading information.*
5. *The GN&C system must identify the location of desired future site(s) relative to the current location.*
6. *The GN&C system must make course corrections to achieve desired future location(s).*

Navigation Architecture and Strategy

For accuracy reasons, it was decided that the best architecture for the navigation system was one based on either a trilateration beacon network or a spaced-based network. Since the communication architecture incorporates a ground network of relays, the best architecture for the navigation system seems to be to piggyback a beacon network onto the communication infrastructure.

For safety reasons, it was decided that each vehicle in the planetary surface mobility system must be able to navigate independently. Thus, each vehicle should be designed such that astronauts can manually navigate based on readings from internal gyroscopes and odometers. In case of failure in these systems, astronauts should also have maps.

Navigation strategy: Hybrid: gyroscope + odometer, map, beacon network

The performance of the navigation system in this design is dependent on the architecture for the communications system. No further analysis was conducted.

Appendix to Section 4.4.1, Thermal Subsystem

The thermal module takes a series of environmental inputs and vehicle heat production in order to size the subsystem. There are three types of environmental heat radiation: solar flux, albedo and infrared (IR) emission that will add heat to the system, so each flux must be quantified. The solar flux is the energy emitted from the sun, which varies inversely with the square of the distance from the sun. On average, the solar flux is 1360 W/m^2 at 1 AU in the direct path of the sun. However, when the camper and ups are shielded from the sun, this value becomes 0 W/m^2, as no sunlight reaches the vehicles. [Larson, 1999]

The second is the albedo, which is the reflection of the solar flux off of the Moon's surface. The average value for the albedo of the moon is an average of 0.12, which means that 12% of the solar flux is reflected back off the surface, and can add heat to the vehicle. [2]

The third is the infrared (IR) emission from the heat of the Moon. This value can be found based on the simple equation:

$$IR\_emit = \sigma T^4 \tag{15}$$

where, σ = Stefan-Boltzmann constant, 5.67 x 10^{-8} W/m^2/K^4
T = surface temperature, K
IR_emit = IR radiation, W/m^2

Assuming the temperature of the Moon to be 160 K [2], the level of IR radiation is then calculated to be approximately 37 W/m^2. Note that this temperature is a worst-case representation of the lunar polar region. The equator of the Moon becomes much hotter during the lunar noon, and would require a different thermal system to radiate heat. During the night, the temperatures drop to 120 K [2], so this value becomes much lower as well.

Not all of this energy reaches the vehicles, as the outer coating of paint has some values of absorptivity and emissivity. For these calculations, the absorptivity was chosen as 0.2 and the emissivity as 0.8. [Larson, 1999] The absorptivity factors the solar flux and albedo heat, while the emissivity factors the IR heat. These numbers cannot simply be added together however, as they do not all strike the vehicle in the same spot. The solar flux strikes mostly the top of the vehicle, and its sides, while the albedo and IR emission mostly encounter the bottom and sides. Given the design of the camper, an assumption was made that the structure was roughly 1/6 area on top and bottom, while the sides accounted for 2/3 of the surface area.

Directly overhead, the vehicle receives 272 W/m^2 from the solar flux with up to 32 W/m^2 from albedo effects on the sides, and 32 W/m^2 from IR emission on the sides and bottom. These numbers were averaged, described in the previous paragraph, so the vehicle receives an average of 90 W/m^2 during the lunar day and 8 W/m^2 during the lunar night.

This day value is then multiplied by the surface area of the vehicle (function input) to determine the environmental heat load. Added to this value is the heat produced by the vehicle (function input) to determine the total heat load.

Some of this heat is lost passively due to the surface of the vehicle. To find the heat lost passively, the effective sink temperature must be defined: [Larson, 1999]

$$T\_eff = \left(\frac{Q_{env}}{\sigma \times \varepsilon} \right)^{0.25} \tag{16}$$

where, T_eff = effective sink Temp, K
Q_{env} = environmental heat load
ε = emissivity, 0.8

The radiation off of the vehicle due to the paint is considered to be:

$$Q\_passive = 0.6 \times SA \times \sigma \times \varepsilon \times (T\_eff^{4} - T_{space}^{4}) \tag{17}$$

where, Q_passive = radiation off vehicle, W
SA = surface area of vehicle
T_{space} = temperature of space, 3 K

The factor of 0.6 accounts for the factor of the paint facing space. The rest of the paint is facing the thermal environment, and does not radiate heat.

The heat that must be reduced for driving time and science time is then computed for this worst-case scenario. From HSMAD [Larson, 1999], the radiator area at the higher latitudes can be found by taking the heat dissipated and dividing by 251.

At this point, the trade analysis is undertaken, as either a vertical or horizontal radiator can be chosen. The vertical radiators dissipate heat bi-directionally, but require extra support mass. The horizontal radiators only dissipate heat in one direction, but have much less support mass. Included with the radiators are heat pumps, plumbing, fluids, and controls. The exact data from HSMAD [Larson, 1999] regarding parametric equations can be seen in the code attached in the appendix.

Additionally, the night time environmental data along with the average science time heat load (assumed to be smaller than driving heat load) were compared from the night time radiation due to paint in order to determine the amount on multi-layered insulation (MLI) needed in this worst case scenario. Using parametric equations from HSMAD [Larson, 1999], this mass and volume were computed as well.

The outputs of the model are as follows:

Table 35 Model Outputs

Variable	Units	Reason
Radiator surface area	m^2	Is design physically feasible?
Thermal volume	m^3	Needed for total vehicle design

Thermal driving power	W	Used for power system sizing, input to MUSE
Thermal science time power	W	Input to MUSE
Pressurized mass	kg	Mass in the vehicle itself to size support system appropriately
Unpressurized mass	kg	Chassis sizing
Total thermal mass	kg	Overall feasibility check on design

The code is set up to run the exact same procedures for Mars. It is assumed that the internal fluid workings would not need to change, just perhaps the size of the radiators. This design should be acceptable anywhere on Mars, and at the poles on the Moon, as mentioned previously at any time. During lunar noon at the equatorial region, an additional thermal dissipation system, such as a reusable phase change system, may be necessary due to the high environmental heat flux. [Eckart, 1999] For Earth, the radiators could be replaced by a convection system, again without disruption to the internal fluid system.

For the unpressurized elements, the design is similar. The same set of equations were used, but some louvers were added to protect sensitive equipment and a small phase change mass for heat dissipation in addition to the small radiators, as seen in Figure 68: LRV thermal system These additions were based on the LRV, with information from a study on the Apollo 15 mission. [Costas, 1972]

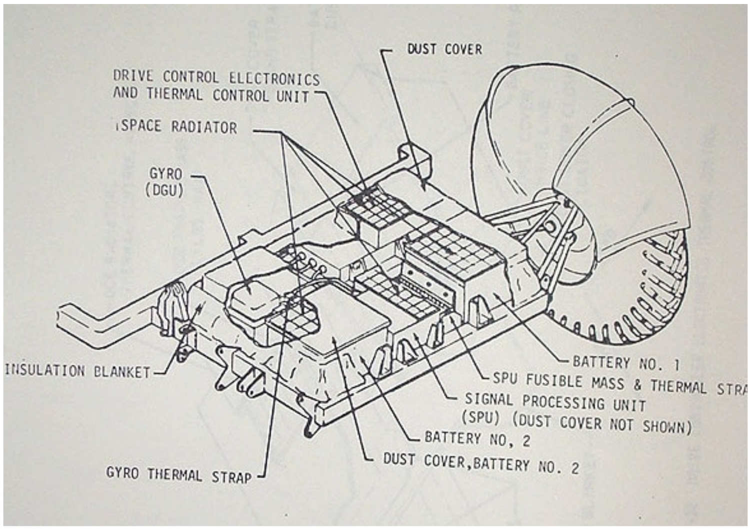


Figure 68: LRV thermal system

Appendix to Sections 4.1-4.3

Payload	**Input**	**Description**
	TVMData.vehicleType	'camper' or 'UPV'
	Output	**Description**
	v_payload.massPress	payload mass that are in the pressurized compartment [kg]
	v_payload.massUnpress	payload mass that are stored on the chassis in an unpressurized environment [kg]
	v_payload.volPress	payload volume that are in the pressurized compartment [m^3]
	v_payload.volUnpress	payload volume that are stored on the chassis in an unpressurized environment [m^3]
	v_payload.drivingPower	payload power required when driving [W]
	v_payload.nightPower	payload power required at night [W]
	v_payload.sciencePower	payload power required when conducting science work [W]
	v_payload.peakPower	payload peak power [W]
Avionics	**Input**	**Description**
	TVMData.vehicleType	'camper' or 'UPV'
	Output	**Description**
	v_avionics.mass	avionics mass [kg]
	v_avionics.volume	avionics volume [m^3]
	v_avionics.drivingPower	avionics power required when driving [W]
	v_avionics.nightPower	avionics power required at night [W]
	v_avionics.sciencePower	avionics power required when conducting science work [W]
	v_avionics.peakPower	avionics peak power [W]
Comm.	**Output**	**Description**
	v_comm.drivingPowerCamper	communication power required when driving for camper [W]
	v_comm.nightPowerCamper	communication power required at night for camper [W]
	v_comm.sciencePowerCamper	communication power required when conducting science work for camper [W]
	v_comm.peakPower	communication peak power for camper [W]
	v_comm.powerATV	communication power required for UPV [W]
	v_comm.massCamper	communication mass of camper [kg]
	v_comm.massATV	communication mass of UPV [kg]
Human Activities	**Input**	**Description**
	TVMData.nCrews	# of crew on traverse per camper
	TVMData.excursionDays	# of days on traverse [days]
	TVMData.nEVAperExc	# of EVAs per excursion [/days]
	v_payload.massPress	payload mass that are in the pressurized

		compartment [kg]
	v_payload.volPress	payload volume that are in the pressurized compartment [m^3]
	Output	**Description**
	v_ha.vol_tot	volume required for human activities [m^3]
	v_ha.living_height	height required for tallest allowed astronauts plus suit [m]
	v_ha.length	length of the cylinder [m]
	v_ha.radius	radius of the can [m]
	v_ha.cntr_to_floor	stance from center of can to floor of living area rectangular box [m]
	v_ha.floorChord	floor width of living area [m]
	v_ha.airlockSurfaceArea	internal surface area of the airlock [m^2]
	v_ha.drivingPower	human activities power required when driving [W]
	v_ha.peakPower	human activities power required at night [W]
	v_ha.sciencePower	human activities power required when conducting science work [W]
	v_ha.nightPower	human activities peak power [W]
	v_ha.wtrConsump	amount of water consumed for human activities [kg]
	v_ha.heatGen	heat generated by human activities [W]
	v_ha.totMass	total mass required for human activities [kg]
Structure	**Input**	**Description**
	v_ha.length	length of the cylinder [m]
	v_ha.radius	radius of the can [m]
	v_ha.cntr_to_floor	stance from center of can to floor of living area rectangular box [m]
	v_ha.floorChord	floor width of living area [m]
	EnvData.ambientPressure	ambient atmosphere pressure [Pa]
	TVMData.structureMaterial	structure material
	Output	**Description**
	v_structure.mass	total structure mass including shell exclude cargo, etc [kg]
	v_structure.vol	total structure volume inside the shell [m^3]
	v_structure.surfaceArea	total surface area need to be covered by radiation protection [m^2]
	v_structure.thermalSA	total surface area for thermal calculations [m^2]
	v_structure.cg	vertical cg from the bottom of the structure storage and equipment [m]
ECLSS	**Input**	**Description**
	TVMData.nCrews	# of crew on traverse per camper
	TVMData.excursionDays	# of days on traverse [days]
	TVMData.nTraverses	# of traverses over the lifetime of the vehicle
	TVMData.regen	water regeneration at base (0) OR on the

		camper (1)
	Output	**Description**
	v_ECLSS.massc	ECLSS mass required on the vehicle [kg]
	v_ECLSS.drivingPowerc	ECLSS power required when driving for camper [W]
	v_ECLSS.nightPowerc	ECLSS power required at night for camper [W]
	v_ECLSS.sciencePowerc	ECLSS power required when conducting science work for camper [W]
	v_ECLSS.peakPowerc	ECLSS peak power for camper [W]
	v_ECLSS.heatPowerc	heat power generated on the vehicle [W]
	v_ECLSS.volcUnPress	ECLSS unpressurized volume required on the vehicle [m^3]
	v_ECLSS.vO2N2c	volume of O2 and N2 on camper [m^3]
	v_ECLSS.vH2Oc	volume of water on camper [m^3]
	v_ECLSS.volcPress	ECLSS pressurized volume required on the vehicle [m^3]
	v_ECLSS.masso	ECLSS mass required at the outpost, including consumables [kg]
	v_ECLSS.powero	power required at the outpost [W]
	v_ECLSS.heatPowero	heat power generated at the outpost2 [W]
	v_ECLSS.volo	ECLSS volume required at thbe outpost [m^3]
Radiation	**Input**	**Description**
	TVMData.radMaterial1	radiation material around whole vehicle
	TVMData.radMaterial2	radiation material around airlock
	TVMData.vehicleType	'camper' or 'UPV'
	v_structure.surfaceArea	total surface area need to be covered by radiation protection [m^2]
	v_ha.airlockSurfaceArea	internal surface area of the airlock [m^2]
	Output	**Description**
	v_radiation.massChassis	radiation mass on chassis [kg]
	v_radiation.massPressurized	radiation mass pressurized [kg]
	v_radiation.totMass	total radiation mass [kg]
	v_radiation.volOuter	radiation volume on chassis [m^3]
	v_radiation.volPressurized	radiation volume pressurized [m^3]
Chassis	**Input**	**Description**
	v_ha.length	length of the cylinder [m]
	v_ha.radius	radius of the can [m]
	v_propulsion.wheelDia	wheel diameter [m]
	EnvData.gravity	gravity [kgm/s^2]
	chassisFrameLoadMass	total mass to be loaded on chassis [kg]
	Output	**Description**
	v_chassis.wheelBase	the length of the chassis [m]

	v_chassis.track	the width of the chassis [m]
	v_chassis.frameMass	total mass of the chassis frame [kg]
	v_chassis.freeVol	amount of free volume in the chassis frame [m^3]
	v_chassis.cg	CG of chassis from chassis bottom [m]
	v_chassis.height	chassis height [m]
Thermal	**Input**	**Description**
	TVMData.radiatorChoice	'vertical radiator' or 'horizontal radiator'
	TVMData.vehicleType	'camper' or 'UPV'
	v_power.thermal	the average thermal power produced by the power subsystem including dissipated power [W]
	v_power.thermalPeak	the peak thermal power produced [W]
	v_structure.thermalSA	total surface area for thermal calculations [m^2]
	Output	**Description**
	v_thermal.chassisMass	thermal mass includes all passive and active system masses [kg]
	v_thermal.pressurizedMass	thermal mass includes all passive and active system masses [kg]
	v_thermal.mass	total thermal mass [kg]
	v_thermal.drivingPower	thermal power required when driving for camper [W]
	v_thermal.nightPower	thermal power required at night for camper [W]
	v_thermal.sciencePower	thermal power required when conducting science work for camper [W]
	v_thermal.peakPower	thermal peak power for camper [W]
	v_thermal.radiatorArea	how large the radiators must be (assumed to be one sided) [W]
	v_thermal.vol	thermal volume [m^3]
Steering	**Input**	**Description**
	TVMData.nSteeredWheels	# of steered wheels
	sprungMass	sprung mass, vehicle body mass [kg]
	v_chassis.wheelBase	the length of the chassis [m]
	v_chassis.track	the width of the chassis [m]
	Output	**Description**
	v_steering.mass	steering mass [kg]
	v_steering.turningRad	turning radius [m]
	v_steering.drivingPower	steering power required when driving for camper [W]
	v_steering.nightPower	steering power required at night for camper [W]
	v_steering.sciencePower	steering power required when conducting science work for camper [W]
	v_steering.peakPower	steering peak power for camper [W]

Propulsion	**Input**	**Description**
	TVMData.nWheels	# of wheels
	transportMass	total mass of all components except wheels and drive motors [kg]
	v_chassis.wheelBase	the length of the chassis [m]
	v_chassis.track	the width of the chassis [m]
	EnvData.gravity	gravity [kgm/s^2]
	EnvData.lurainType	terrain type (1:Hummocky upland, 2:Rougn mare, 3:Roungh Upland, 4:Smooth mare)
	Output	**Description**
	v_propulsion.drivingPower	propulsion power required when driving for camper [W]
	v_propulsion.nightPower	propulsion power required at night for camper [W]
	v_propulsion.sciencePower	propulsion power required when conducting science work for camper [W]
	v_propulsion.peakPower	propulsion peak power for camper [W]
	v_propulsion.driveMass	mass of drive motor [kg]
	v_propulsion.wheelMass	mass of wheels [kg]
	v_propulsion.mass	propulsion mass [kg]
Power	**Input**	**Description**
	TVMData.vehicleType	'camper' or 'UPV'
	TVMData.driveTime	driving time per day [hr/day]
	TVMData.excursionDays	# of days on traverse [days]
	TVMData.driveDays	#r of consecutive driving days [days]
	TVMData.atv_energy	the energy required per UPV per science day [W-hr]
	TVMData.atv_number	the number of UPVs used per science day
	drivingPower	driving power of every module [W]
	nightPower	night power of every module [W]
	sciencePower	science power of every module [W]
	peakPower	peak power of every module [W]
	Output	**Description**
	v_power.thermal	the average thermal power produced by the power subsystem including dissipated power [W]
	v_power.thermalPeak	the peak thermal power produced [W]
	v_power.water	the total amount of water produced by the fuel cells by the end of the mission [kg]
	v_power.energy	the total energy capacity of the system
	v_power.massATV	the power mass that is on the UPV [kg]
	v_power.massCamper	the power mass that is on the camper [kg]
	v_power.powerCamper	the power production on the camper [W]
	v_power.powerATV	the power production on the UPV [W]

Suspension	**Input**	**Description**
	sprungMass	sprung mass, vehicle body mass [kg]
	tireStiffness	tire stiffness [N/m]
	v_propulsion.wheelMass	mass of wheels [kg]
	Output	**Description**
	v_suspension.springStiffness	spring stiffness of suspension system [N/m]
	v_suspension.dampCoeff	damping coefficient of the shock absorber [kg/s]
	v_suspension.suspensionMass	suspension mass [kg]

Appendix to Section 4.4.2, Radiation Subsystem

The radiation system is very dependent on environmental factors, namely Galactic Cosmic Radiation (GCR) and Solar Particle Events (SPE), which are commonly referred to as solar flares. The GCR is a relatively constant background source, although it varies with the solar maximum and minimum. SPEs happen more frequently at the maximum of the solar 11 year cycle, but are generally negligible to nonextistent during the solar minimum. [Larson, 1999] Each of these factors presents a different problem, which will be discussed further here to explain the choice of trades.

While 95% of the GCR is light-weight atoms easily stopped by shielding, the remaining portion (called HZE particles) are much heavier nuclei. When they interact with the typical shielding used on Earth, these ions start to cascade, creating an even worse radiation environment. Studies have shown that materials with high hydrogen content provide the best shielding from GCR, so water, liquid hydrogen, liquid methane, and other high hydrogen content materials are being considered for a long-duration space mission. [Larson 1999] A polyethylene (another high H material) shield was tried on ISS, but proved ineffective. [SpaceToday 2002]

SPEs are mostly high energy protons and electrons, with some additional heavier atoms that are created in the sun's atmosphere. They do not last for very long periods of time, but can have very high flux values (up to 4.5 mW/m^2), which are quite dangerous to human beings. While typical shielding in the aerospace industry, such as aluminum, is effective against these natural phenomena, the resulting mass is quite large. Ideally, the camper would not need any shielding at all, and the astronauts could simply return to base. [Parnell 1997] However, the lead time when scientists can predict these events is very small. Once thought to be on the order of hours, an event in January of 2005 reached Earth 15 minutes after it was detected. [Caron 2004] If astronauts are traveling up to 100 km away from their base, then the pressurized element must have some shielding. The unpressurized elements do not have shielding, as it is hoped that the lead time will have increased to the point that astronauts can have at least 3-4 hours of warning.

NASA has developed levels of acceptable radiation, outlined in the NASA-STD-3000. The critical number analyzed here is a maximum 50 REM exposure per year. (Additionally, the exposure over a month-long period is 25 REM, and the lifetime value a factor based on the astronaut's age. All these numbers need to be evaluated for future, higher fidelity designs that take into account transit and base radiation levels.) [NASA-STD-3000]

The initial design called for two levels of shielding: one thin layer around the top and sides of pressurized shell for protecting against GCR and a much larger layer to protect against SPEs around the airlock, which would be used as a shelter in case of a solar particl event. However, later decisions were made to assume that the astronauts could sleep in the airlock, which removed the need for the additional GCR shielding, which was on the order of 750 to 1000 kg originally.

From NASA-STD-3000, the average GCR at 1 AU was found to be 55 REM. The SPE was modeled after the six major events in 1989, which should be a conservative estimate. The shielding values are in g/cm^2, which is the areal thickness. This is the mass per cm^2 of surface area that an incoming particle would encounter. Therefore, across these thicknesses, the mass is constant no matter the material, making it a better comparison metric than a simple linear thickness. From the work of Wilson, et al. a figure was found that identified various materials' ability to stop GCR [Wilson 1997]. The Lunar Base Handbook had a figure giving similar data for the 1989 SPEs. [Eckart 1999]

In addition to the radiation shielding, the material already in the camper can help stop radiation. It was assumed that the airlock itself provided 4 g/cm^2 in material. The entire vehicle structure, thermal components, etc., were assumed to stop an additional 5% of the SPE, a conservative estimate. Being low hydrogen materials, they would not stop any GCR, but rather cause cascading. The GCR total (55 REM) was divided by 1.75 to account for this occurrence, instead of by 2, since the Moon (or Mars) blocks half of the radiation value.

The different materials tried are seen in the following table:

Table 36 Trade Options

Water	Liquid hydrogen
Lithium hydride	Liquid methane
Aluminum	Polyethylene

Each material was incremented by a factor of 0.5 g/cm^2 until it was able to reduce the GCR and SPE radiation to less than 50 REM, given the constraints discussed previously. The code can be seen in the appendix.

The outputs of this code are simply the radiation mass and volume, based on covering the top and sides of the airlock, with more material needed on top than nearer the bottom.

For Earth, no shielding is necessary, so this subsystem should be designed to be easily removable. The GCR on Mars is approximately 58 REM, but the SPE is reduced due to the increased distance from the sun. The values for Mars for the SPE were simply reduced by ¼ as a conservative estimate, since very little is known about how much the atmosphere and magnetic field protect the planet. [Beaty 2005] A delta can be calculated here so any changes can be made for the new environment.

Overall, a number of questions need to be addressed before a decision can be made on the realistic shielding for exploration.

References:

1. HSMAD (Larson, 1999)
2. Lunar Base Handbook (Eckart, 1999)
3. Mobility Performance of the Lunar Roving Vehicle: Terrestrial Studies, aka the LRV Bible (Costas, 1972)
4. http://www.spacetoday.net/Summary/1262

5. Parnell, Thomas and John Watts. “Radiation Effects and Protection for Moon and Mars Missions” Marshall Space Flight Center. 1997
6. Caron, Ryan. “Radiation Shielding for manned missions to Mars.” Worcester Polytechnic Institute. 2004.
7. NASA-STD-3000. http://msis.jsc.nasa.gov/sections/section05.htm.
8. Wilson, J.W., F. A. Cucinotta, M. H. Kim, and W. Schimmerling. “Optimized Shielding for Space Radiation Prtoection.” 1st international workshop on Space Radiation Research and 11th Annual NASA Space Radiation Health Investigators’ Workshop., 1997.
9. David W. Beaty (Mars Program Office-JPL/Caltech), et al. “An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars.” 2005

Appendix to Section 4.6, CAD Drawings

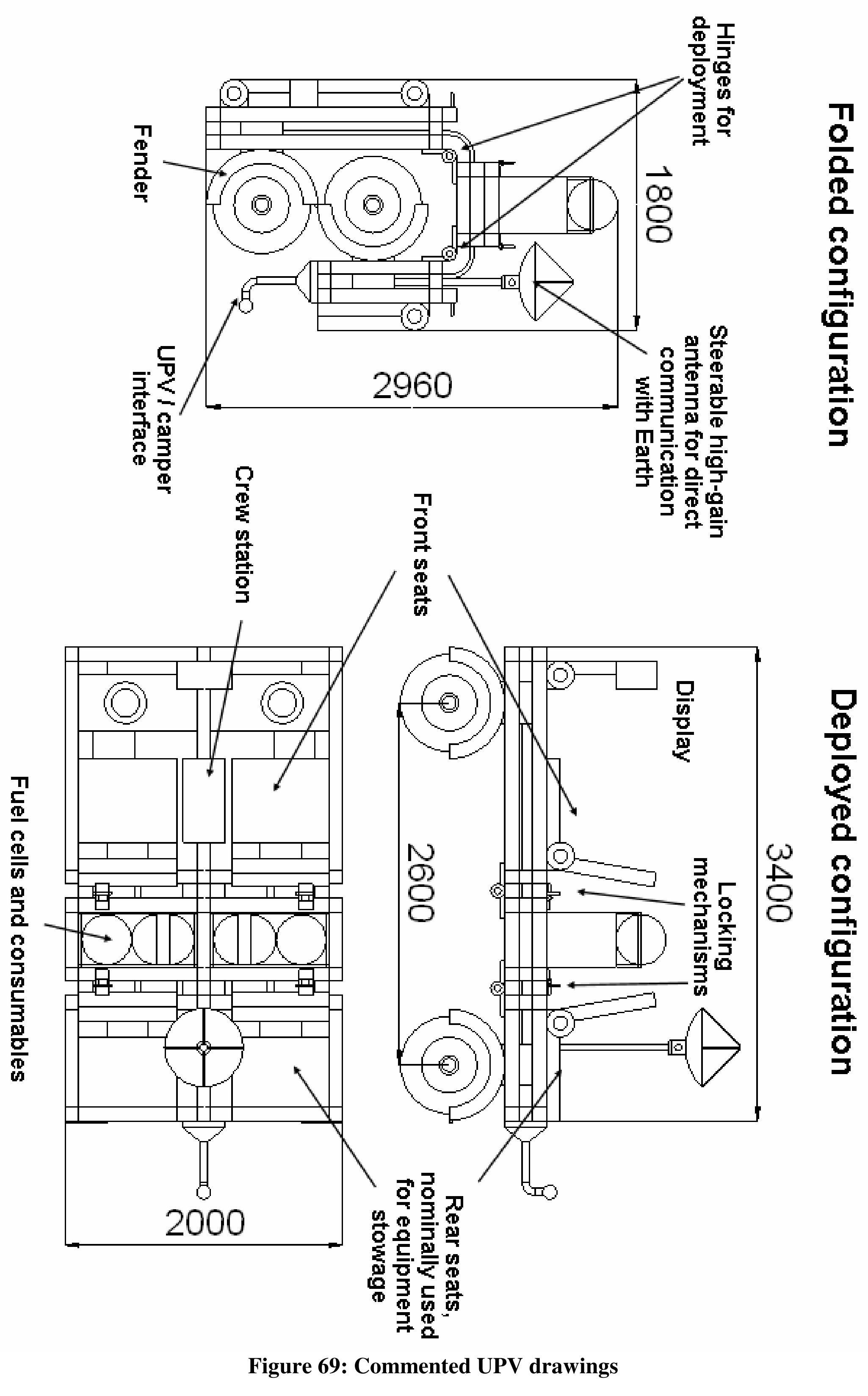


Figure 69: Commented UPV drawings

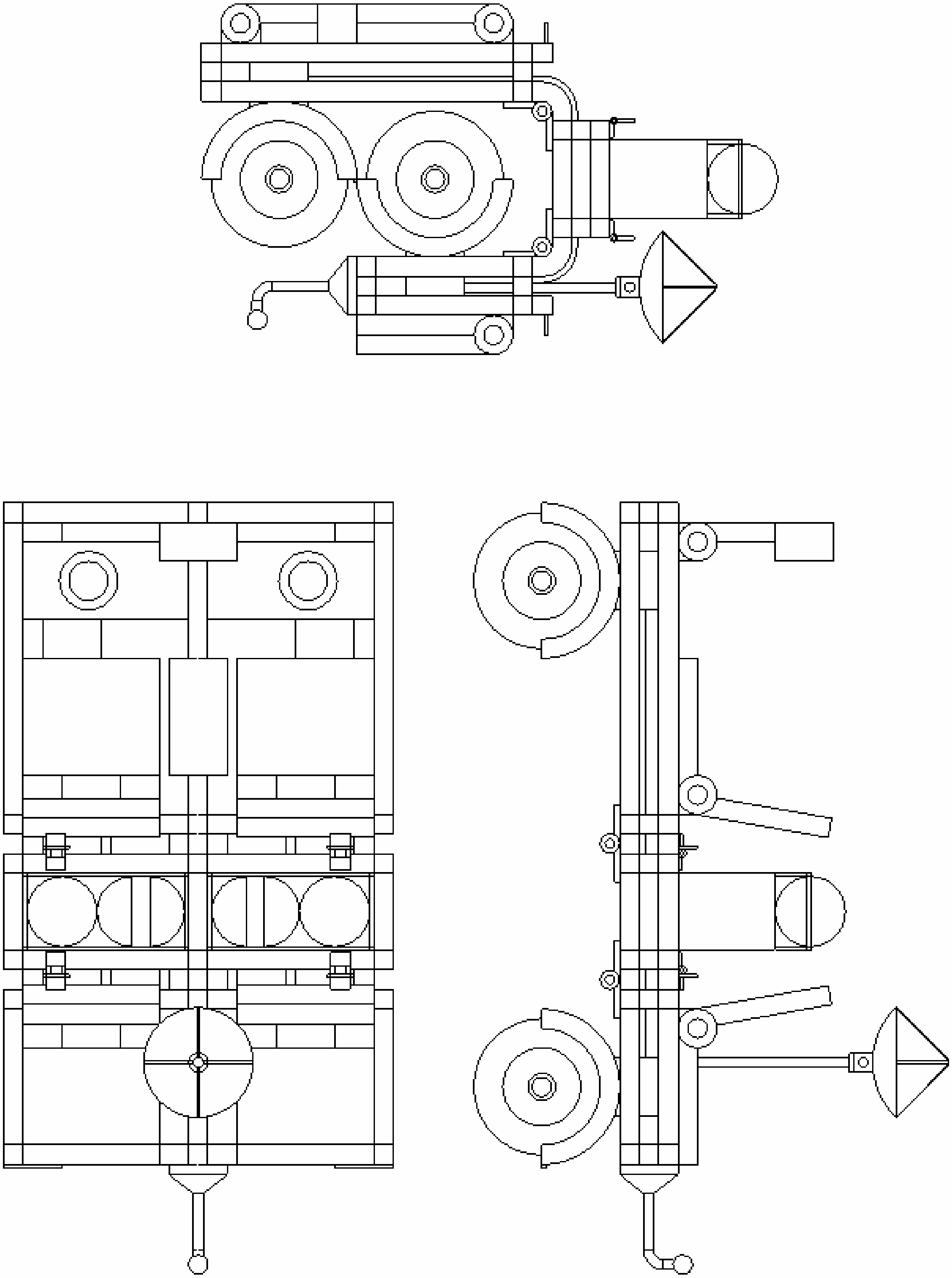


Figure 70: Uncommented UPV drawings

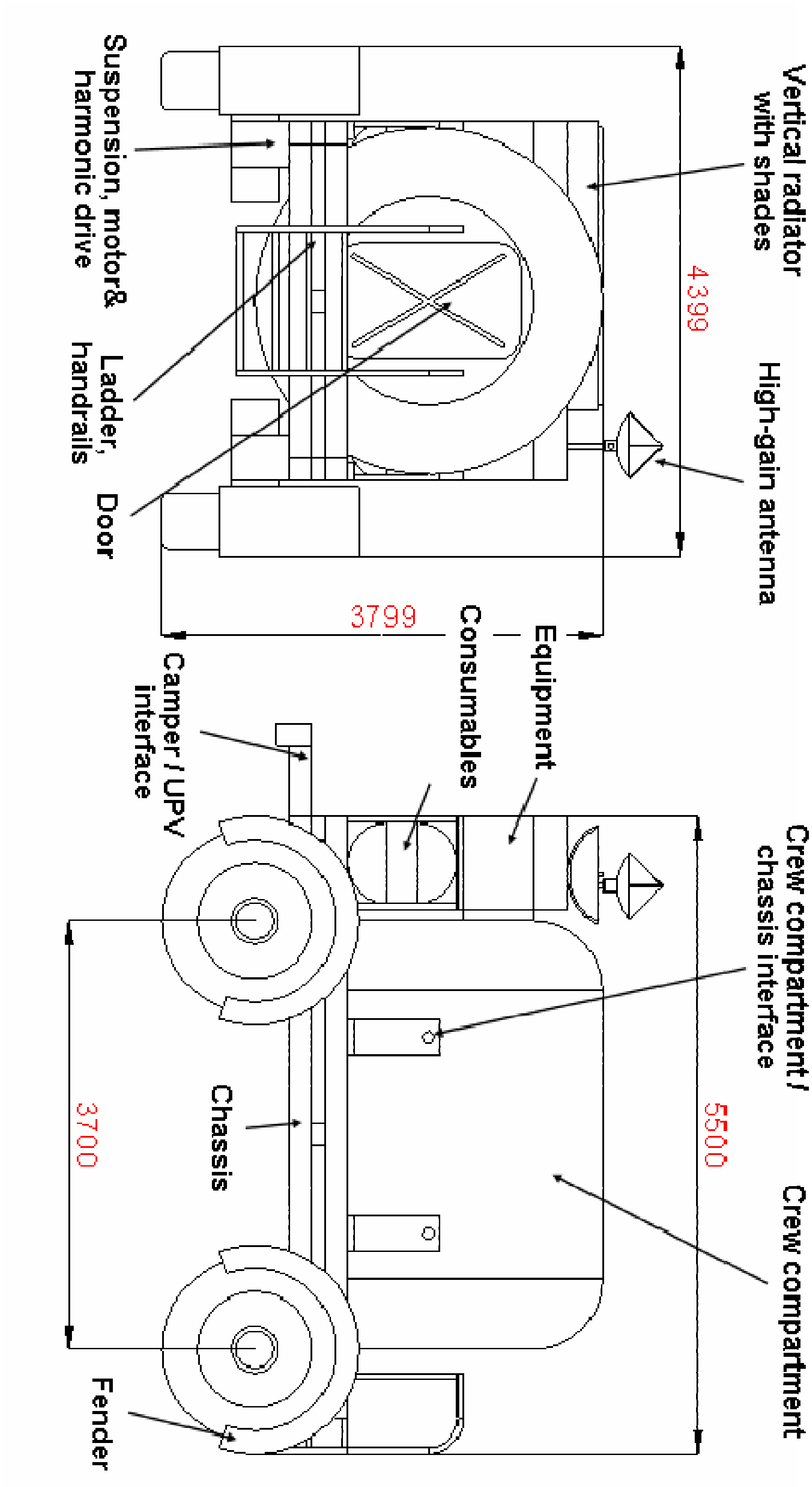


Figure 71: Commented camper drawings

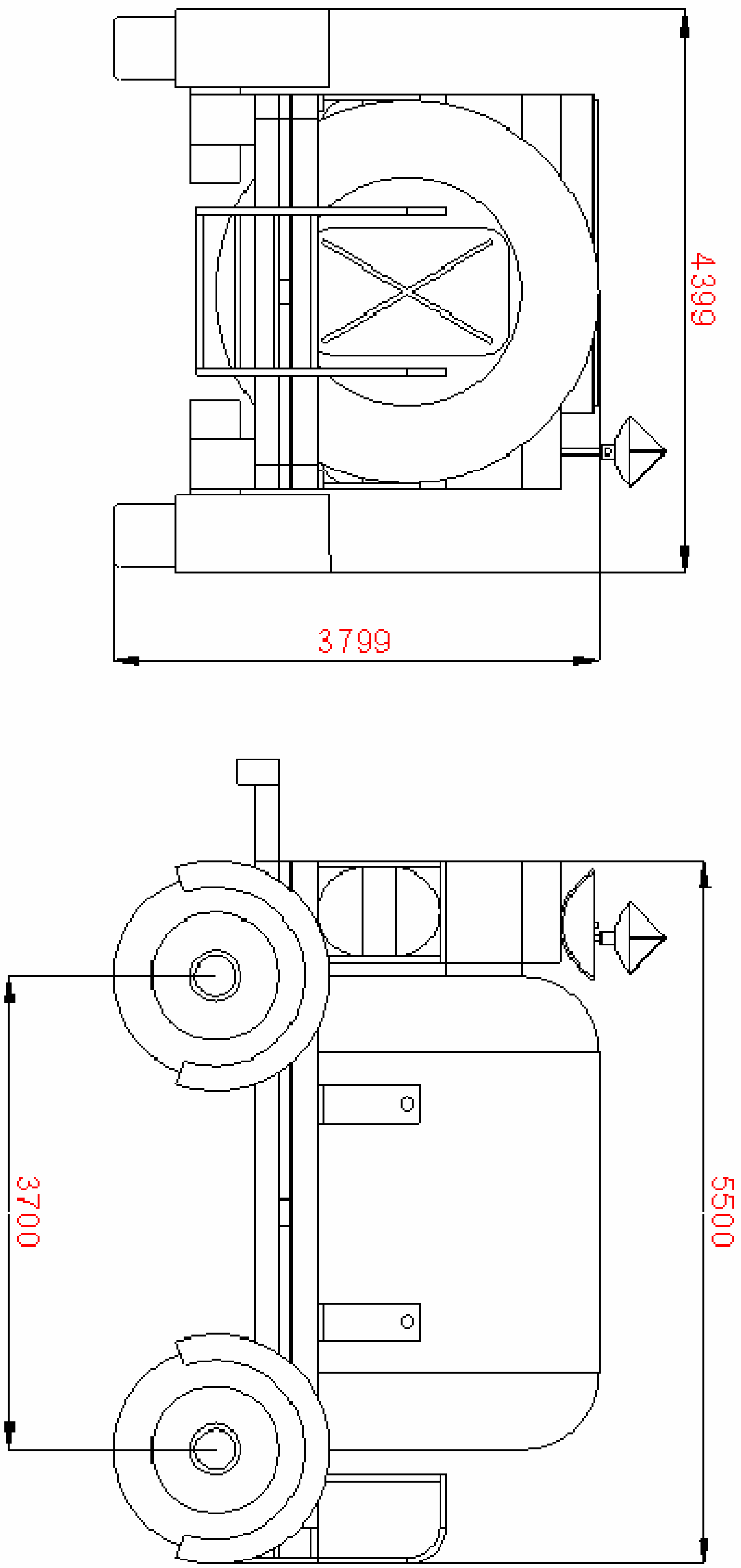


Figure 72: Uncommented camper drawings

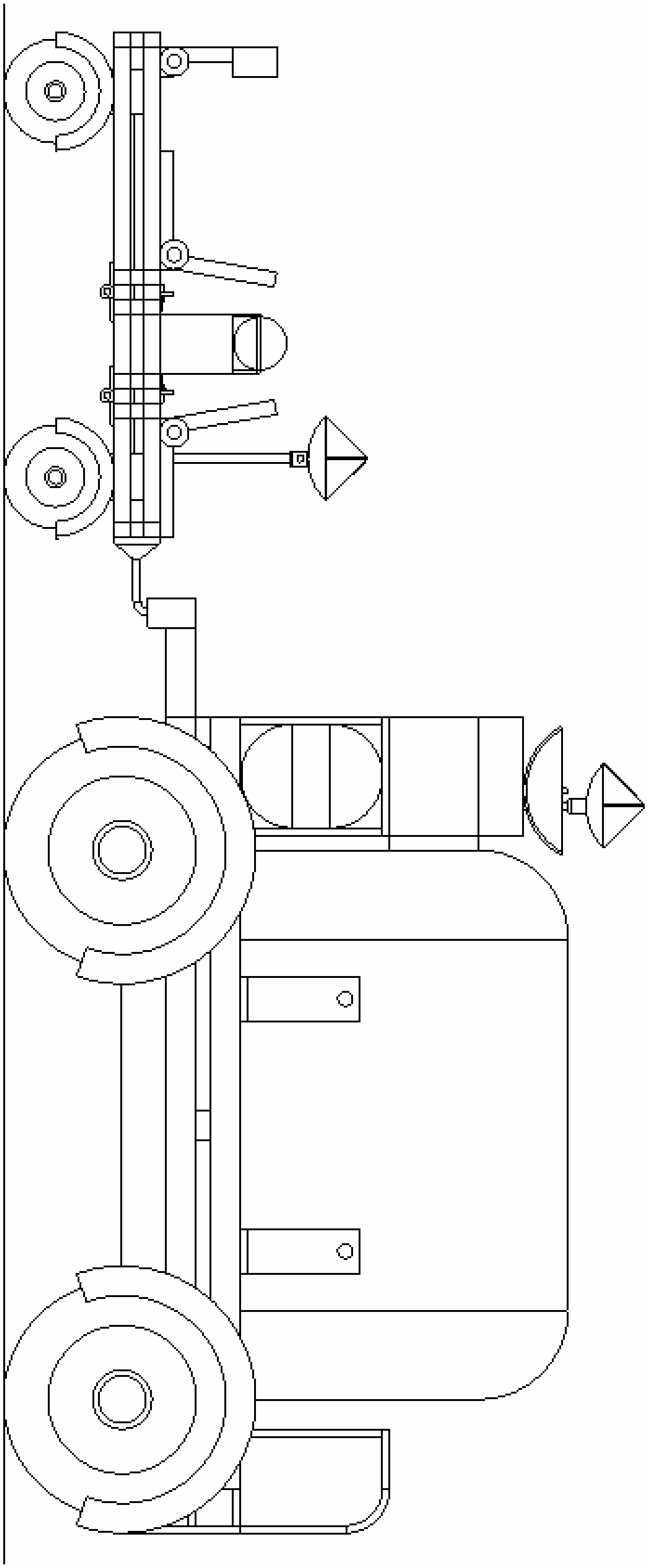


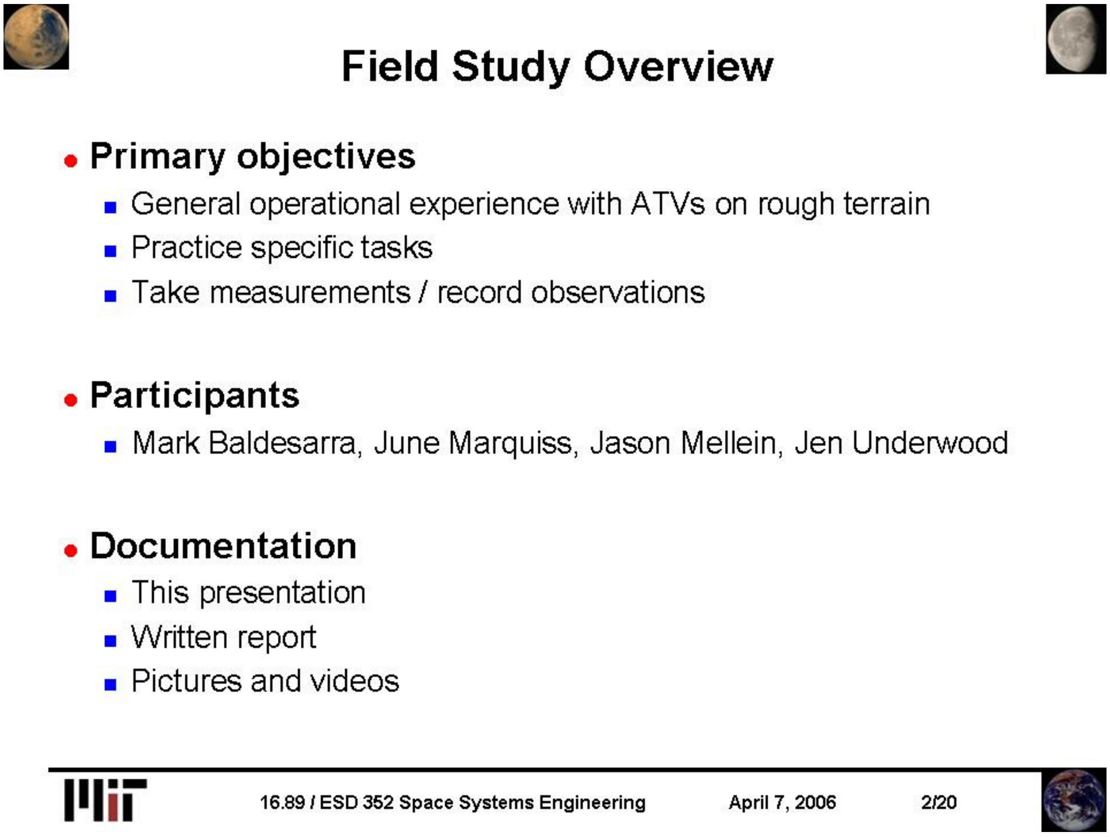
Figure 73: Drawing of camper / UPV combination

Appendix: Maine-Moon-Mars Field Expedition Debriefing

Maine - Moon - Mars Field Study

April 1-2, 2006

Presented by Mark Baldesarra, April 7



Field Study Overview

- **Primary objectives**
  - General operational experience with ATVs on rough terrain
  - Practice specific tasks
  - Take measurements / record observations
- **Participants**
  - Mark Baldesarra, June Marquiss, Jason Mellein, Jen Underwood
- **Documentation**
  - This presentation
  - Written report
  - Pictures and videos

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Weather and Location

- **Weather Conditions**
  - Rain prior to arrival: terrain was damp
  - Excursion 1: 7°C (45°F), scattered showers, overcast
  - Excursion 2: 11°C (51°F), 99 kPa, clear skies and sunny

- **Location**
  - Farmington, ME near Clearwater Pond
  - ~4 hours from Boston

Vehicles

- **Vehicle 1**
  - Yamaha Kodiak 4x4 400 ATV
  - Jason and June (passenger/driver)
  - Equipped with (broken) 900 kg winch
  - Storage box

- **Vehicle 2**
  - Kawasaki 4x4 300 ATV
  - Jen (driver) and Mark (passenger)
  - Windshield
  - Cargo capacity of 65 kg

Vehicles

- **1991 Toyota 4Runner**
  - Transport between Boston / Maine
  - Could not use it for off-roading due to rain-soaked trails
- **Trailer**
  - Standard towing attachment
  - Attached to Vehicle 1 or 2
  - Rocker-bogie suspension
- **Vehicle 3**
  - Honda 2-wheel drive (3 wheels)
  - Hollis (driver, guide)

Excursions Overview

- **Excursion 0: Roadside Ditch (3 min)**
  - Attempted to traverse a ditch with 4Runner
  - Damage to transmission and vehicle structure
- **Excursion 1: Operations (2 hr)**
  - Familiarization with area
  - Practice driving
  - Planning for Excursion 2
- **Excursion 2: Experiments (2.5 hr)**
  - Trailer towing
  - Contingency operations
  - Speed and distance measurements
  - Photo / video / written documentation

Terrain Types


Woods


Fields


Shale


Road

Terrain Effects

- Obstacles (Crevasses, Boulders, Craters)

Ditches	0.5m – 1m width Up to 0.5 m deep
Rocks	Up to 0.5m diameter
Stumps	0.2 – 0.5m diameter
Puddles	Up to 1.5 m diameter

  - Also: general uneven terrain
  - Restricted to trails in woods
  - Obstacles on the same scale as wheels can jostle the vehicle
  - Watch for undercarriage damage: could cause problems later on

Terrain Effects

- **Mud (Dust)**
  - Mud kicked up to 1m high from vehicles
  - Windshield gets dirty and obscures view
  - Inline driving needs greater distance between vehicles to avoid trailing plume

Driving Operations

- **General Observations**
  - Max speed limited even on smooth terrain: small, infrequent craters will jostle the vehicle
  - Reduce steering feedback: driver fatigue
  - 4-wheel drive very useful for traction and stability
- **Astronaut Fatigue**
  - Riding for two hours straight was very tiring (without a space suit)
  - Need shifts and rests for long non-stop traverses
- **Overworking the Vehicle**
  - Perceptions of terrain not always accurate
  - Know your vehicle limits (i.e. training)
  - Dynamic feedback on current grade
  - LIDAR system to analyze upcoming terrain?

- **Question: Can you perform science investigation while driving?**

Vehicle Design

- **Transmission**
  - Reverse gears are important!
  - Reversing trailer difficult, especially on rough terrain
  - Multiple gears: low gears needed for difficult terrain, high gears for speed
  - Potential dust contamination problem

- **Turning Radius**
  - Important for obstacle avoidance
  - Dependent on distance between hitch and trailer (tongue)
  - Shorter trailer tongue = shorter turning radius but possibility of jackknifing

- **Vehicle Components**
  - Methods to secure astronauts during traverse
  - Separate emergency fuel reserve if main power / fuel source is damaged

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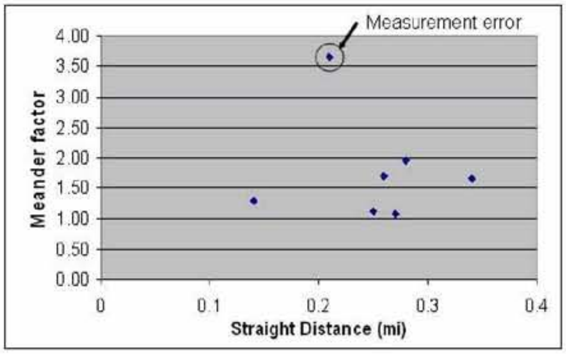
Speed and Distances Travelled

- **Used GPS for measurements**
  - Time trials on various terrain
  - Measurements during traverses
  - Coordinates of science sites
  - Meander factors



Terrain Type	Maximum Speed
Wood	5 km/h to 10 km/h
Field	25 km/h to 32 km/h
Road	40 km/h

Multi-Vehicle Coordination

- **Driving Configuration**
  - Drive inline if the terrain was uncertain or allowed for only one path
  - Drive tandem otherwise (faster)
- **Following Distance**
  - Minimum distance restricted by dirt plume, braking distance
  - Maximum distance restricted by line of sight, path following
- **Navigation**
  - Guide: stop and explain area up ahead
  - Without a guide, would need maps and more frequent stops to plan traverses over difficult terrain
- **Communications**
  - Some communication while moving (i.e. requests to slow down)
  - Detailed planning while stopped: unable to do en-route

Modular Components

- **Winch / tow equipment**
- **Navigation device**
  - Take readings at site
  - Emergency use during walk-back
- **Life support / fuel supplies**
- **Cargo compartments**
- **Wheel / motor units**
  - Switch to neutral if malfunctions
- **Video equipment**
  - Mounted to vehicle during traverse, removed at science site

Towing Operations

- **Driving Properties**
  - Sluggish acceleration
  - Shift to lower gears to pull up slopes: speed alone may be insufficient
  - Extended stopping distance
  - Trailer doesn't follow the towing vehicle exactly: may catch onto obstacles

- **All-powered wheels: useful on steep grades or difficult terrain, but may not always be necessary**

- **Safety**
  - Need system to monitor stability of trailer
  - Consider tip-over failures if trailers are top-heavy
  - Quick release method without leaving the vehicle

Contingency Operations

- **Equipment**
  - Winch, tow rope
  - Hardpoints at front and back
  - Ability to connect at other points to recover after tip-over
  - Run structural analysis on tow cable

- **Operations Test**
  - Front wheel stuck in crevasse
  - Attempted to tow forwards
    - **Need throttle?**
    - **Need steering?**
    - **Need a person on the ATV?**

Contingency Operations

- **Test Results**
  1. Steering and throttle: extracted easily
  2. No steering or throttle: rope snapped
  3. Assisted, no throttle: can't get out – had to use the throttle

- **Lessons learned**
  - Sometimes need throttle to extract
  - Consider different vehicle orientations for extraction (pull from back)
    - **Terrain may not allow this**
  - We were cautious with rope since it snapped earlier: need proper cable

---

Problems Encountered

1. **Fuel contamination**
   - Water in fuel system, caused vehicles to stall (think dust)
2. **Fuel exhaustion**
3. **Tipping**
   - Extreme terrain or travelling too fast
4. **Vehicle Collision**
   - Following vehicle bumped the leading vehicle
   - Followed too close, tried to stop on slick terrain
5. **Physical injury during science operations**
6. **Broken equipment (winch)**
7. **Stuck in ditches**
8. **Positioning towed vehicle upon stop / reversing**

Summary

- **Results of Field Study**
  - Gained insights into using ATVs on rough terrain
  - Better sense of excursion operations
  - Refine architectural ideas
  - Areas to investigate during detailed design

- **Acknowledgments**
  - Hollis, our guide
  - Dorri and Robert, for hosting us
  - Profs. de Weck, Hoffman, Crawley, for funding and support