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MOBILITY OF LARGE MANNED ROVERS ON MARS

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A study of a number of earth analogs for large, heavy, long range offroad vehicles generates useful inputs for rover design on Mars. An investigation into the types of suspensions available, wheeled and tracked, looks at their suitability for Mars use. Analysis of the mechanics and dynamics of power requirements indicates that motive power for a given speed should scale with the local gravity. Relative stability and mobility of vehicles are examined and the lesser stability of Mars vehicles quantified and shown to be within workable limits. Rover propulsion options are examined, investigating characteristics of possible fuel cell and internal combustion powertrains. Finally, three sample long range expeditionary rovers are described with estimated traverse ranges of over 5,000 km.

1. INTRODUCTION

Manned exploration of the surface of Mars will be critically dependent on the capabilities and safety of the surface transport vehicles available. Previous works have analyzed manned rovers [Clark 96; French 89, McCann 89, Zubrin 92, 96] from some high level assumptions to derive basic information. I feel it is important to analyze Mars rovers by starting with information known about similar vehicles used on Earth, their performance and drawbacks. Fortunately, a large class of heavy off road vehicles exists and is readily documented [Janes 97]: military vehicles, tracked and wheeled, exist in profusion and are good models in many ways for the types of mobility that explorers are likely to need on Mars. This paper will continue to build up performance and other requirements for rover design from low level analysis moving upwards, while assuming little about the end vehicles. It is hoped that this analysis will be useful for the design and tradeoff of any sized and mission manned Mars rover.

2. SUSPENSION CLASSES

There are two major types of vehicle support and suspension systems: tracked and wheeled. There are a few alternative systems (walkers, hoppers, and the like) which are not yet in viable use on Earth. Lacking any practical field experience with the alternatives, we will limit our choices to tracked and wheeled.

Tracked vehicles utilize a continuous, articulated belt made up of generally flat contact plates as the ground contact surface, providing steady support on shifting and weak ground surfaces and effectively distributing loads imposed by heavy vehicles. Tanks, some other military vehicles, and commercial bulldozers are examples.

A number of prior papers have examined the “loop wheel” concept [French 89, McCann 89]; based on practical considerations, this is a special case of the tracked vehicle type. The prior investigations rejected loop wheels as insufficiently robust for long term usage on Mars, and their lack of field experience on Earth to disprove that conclusion leads this author to agree that they are not at this time worth consideration as a viable option.

Wheeled vehicles use multiple tires to contact the ground, giving less contact surface area, higher ground pressure and lower performance on very weak ground surfaces. Cars, trucks, and numerous other vehicles are examples.

Wheeled vehicles have additional detailed design choices in the type of tire used, with the usual options investigated in the past being pneumatic or wire cage tires. Solid tires utilizing elastomeric materials also are used in some applications on earth (such as armored cars) and are of interest in Mars applications due to ruggedness and reliability.

A fair rule of thumb from analysis of a number of vehicles is that a tracked suspension will weigh roughly 15% of overall vehicle weight and a wheeled suspension roughly 10% of overall vehicle weight at 1G. It is likely that this can scale with vehicle weight (i.e. with local gravitational level) rather than vehicle mass.

3. MOTIVE POWER AND SPEED

In most vehicle power calculations in earthbound environments, power is related to velocity squared, cubed, or to the fourth power, depending on the details of how drag interacts with the vehicle type and speed range.

For wheeled and tracked vehicles, examination of 53 representative tracked vehicles and 22 wheeled vehicles [Janes 97] showed that the listed road speed was well predicted by the formula:

speed = sqrt(p/w) × Ft

Where speed is the square root of the power to weight ratio (in kilowatts per ton) times a factor based on the type of suspension (wheeled or tracked). Derived suspension type factors are:

Tracked: Ft = 15.7 ± 3.0
Wheeled: Ft = 24.7 ± 2.0

Horsepower per ton are used by [Janes 97] and other publications, but the calculations are being performed here in kW/ton as units remain more consistent throughout performance calculations.

The power to weight ratios for the vehicles studied ranged from 12.5 to 34.0 hp/ton (9.3 to 25.4 kW/ton) for tracked, with the average of 21.16 hp/ton and standard deviation 4.75 (15.78 ± 3.54 kW/ton); and 14.6 to 34.6 hp/ton (10.9 to 25.8 kW/ton) for wheeled, with an average of 19.34 hp/ton and standard deviation 6.1 (14.42 ± 4.55 kW/ton). The question now becomes what is the significance of this general finding for Mars vehicles and design tradeoffs?

The Mars environment is characterized by a near total lack of atmosphere (5-8 millibars avg), lower gravity (3.8 m/s^2), and a surface that is apparently relatively smooth at medium and small topology scales but rough in fine detail (many rocks of scales 1-100 cm). Without examining the effects of rocks in detail, the other effects should serve to reduce the power used to traverse terrain. The question becomes, to what degree does reduced gravity and atmosphere reduce the power consumption?

One case of interest is hill climbing. In this movement, a vehicle is ascending a sloped surface, spending propulsive power to increase altitude primarily.

The definition of power (force × distance / time, in metric units n × m / s) indicates that power spent in hillclimbing should be proportional to the local gravity if distance and time are kept constant, as force (mass times gravity force) is proportional to local gravity. So 0.38 of the power required on Earth is needed for hillclimbing on Mars.

Power used in friction within the propulsive system also may scale with local gravity. The relevant analysis factors here, frictional coefficients, rotational velocity, and surface area of bearings and other friction surfaces, do not directly change due to a lower gravity environment. However, if we assume that suspension system mass is proportional to vehicle weight and not mass, then as the vehicle weight decreases in local gravity then the required mass, and thus area of bearings and other contacting surfaces, should proportionally decrease.

I believe that a complete and detailed analysis of the mechanics and dynamics of vehicle motions in reduced gravity is called for, but the preliminary indications are that performance scales inversely with local gravitational acceleration.

4. MOBILITY

A number of tradeoffs exist in designing vehicles for rough terrain operations.

One key factor is ground pressure, the average force imposed by the vehicle over the contact area between it and the ground (the tread footprint area, or the contact footprint of the tires for wheeled vehicles). Vehicles with higher ground pressure tend to be more efficient on flat, hard surfaces, but are easier to bog down and get stuck on soft surfaces such as sand or mud. Existing tracked vehicles have ground pressures ranging from 0.75 to 1.05 kg/cm^2 (this being the standard unit used in [Janes 97]) for tanks and 0.55 to 0.75 kg/cm^2 for other tracked vehicles. Unfortunately, ground pressure is not commonly listed for wheeled vehicles, so direct comparisons are not available.

It will be easier to achieve low ground pressure at Mars, if desired, due to the lower gravity. This will be counterbalanced by a desire to reduce suspension mass and vehicle mass overall.

Acceptable ground pressure ranges depend on a number of factors. Foremost are the average and extreme values for soil type the vehicle will have to operate over. Of secondary importance is the capability of the crew to extract the vehicle should it become mired in loose or weak soil. A merely embarrassing situation for a military vehicle on Earth, remedied by calling in a recovery vehicle or other equipment, might be unsalvageable on Mars due to lack of support or EVA gear mobility and dexterity limitations.

The type of suspension system, wheeled or tracked, also significantly affects the mobility of the vehicle. Tracked suspensions are slower and heavier, but give reduced ground pressure and improved rough terrain mobility. Wheeled suspensions are faster over good terrain, but slower over bad terrain. Both are vulnerable to sufficiently large rocks or other obstructions, which will be discussed in more detail in the following section. The NASA Reference Mission [Weaver & Duke 93] and prior rover papers [French 89, McCann 89] with pre-Pathfinder and MGS data concluded that tracks were not optimal choices, but the topology evident in publicly released images from those missions to date appears to be less conclusive. Until further data is available, both types of suspension should be considered as alternatives.

5. MOBILITY, RELIABILITY AND SAFETY

A number of environmental factors influence the reliability of Mars surface vehicles. At the micro scale, Mars has dust on the surface, which would be kicked up by vehicle motion and will cause wear in rotating mechanisms and other problems. At mid-scales, rocks may damage the suspension or vehicle proper should it bottom out or strike a sufficiently large one. At larger scales, the topology has sufficient vertical profile that vehicle overturn incidents are possible, which might well be catastrophic. There is no readily apparent non-life-support significant vehicle design impact of the atmosphere, the insolation, or radiation environment, except that for long duration rovers some protection in case of solar particle events is a wise precaution.

Surface Features

Rocks much smaller than the tire or tread width largely do not affect motion, but those of the same scale as the track or tire can impede progress or damage the vehicle if it hits them at much speed. Unfortunately, visual examination of Viking 1 and 2 and Mars Pathfinder imagery indicates that rocks of sufficient size to damage vehicles are plentiful, at least in those areas. Based on thermal analysis of the surface, a high proportion of the surface area of Mars is covered by rocks 10 cm in diameter or larger [Christensen 92], typically 6% but in a number of interesting areas (such as north and east of Valles Marineris) at a more significant 15-20% coverage. Determination of actual diameter distribution from thermal inertia data is difficult, as thermal inertia of rocks 10 cm and up is roughly constant. Numerous rocks of 25 cm and larger diameter are visible in surface imagery, with some 1m rocks and some suggestion of larger boulders or outcroppings of bedrock of multi-meter scale.

The size range distribution indicates that rocks and boulders on the Mars surface are going to be a significant hindrance and design constraint on any Mars rover. Rover tires considered for prior designs tend to be 1 m to 2 m in diameter, with width of 0.25 m to 0.5 m. Treads would have similar 0.65 m to 1.5 m height and 0.25 m to 0.65 m width. Roughly speaking, surface rocks with sizes between 0.1 and 0.3 of the width of the contact surface are a control hazard and significant maintenance wear, while larger rocks are a threat to the integrity of the suspension, possibly causing damage (wheel destruction, suspension arm damage, or "thrown" tread, coming loose from the tread wheels). A preliminary comparison of the surface topology with available suspensions indicates that even in average surface areas, vehicles are going to be operating in dangerous conditions with significant risk of damage due to surface rocks. Vehicle operating speed restrictions, structural design requirements, and maintainability requirements need to be investigated in more detail and will pose significant operational constraints.

Vehicle Stability

Vehicle overturn accidents happen due to a number of causes, but they all come down to one simple criterion: the vehicles' center of gravity (COG) is rotated past the edge of the vehicles' ground footprint and thus then provides an overturning moment. Once the COG has passed that point, overturn is unavoidable.

There are three main causes of such accidents: the vehicle tipping due to terrain, due to rotational impulse, or due to sideways motion. Most actual overturns are due to a combination of two or more factors occurring simultaneously, but a detailed analysis of the interactions is relatively difficult. We will consider them separately and then analyze the interactions.

Tipping due to terrain is relatively straightforward: the vehicle moves onto a slope of sufficient inclination that the COG passes outside the contact footprint, and the vehicle then overturns. The mechanics of such overturns are the same under fractional gravity as on Earth, though the dynamics are slower, and the risk and design impact are not affected.

Tipping due to rotational impulse is relatively rare on Earth. While most drivers, particularly those with off road or rough road experience, are familiar with the phenomena of running over a bump that caused one side of the vehicle to momentarily lift off the surface, such encounters rarely result in rollovers on Earth. On Mars, the situation is somewhat different. An analytical solution is difficult for this problem, but computational simulation provides some useful results. I simulated such overturns, keeping the wheel to COG distance constant at 2.0 meters, varying track width and COG height such that the angle between horizontal and the line from the tire to the COG varied from 0 to 40.5 degrees thus simulating varying initial slope and initial height of center of gravity, and found the following angular velocities needed to overturn the vehicle:

Table 1

From this we deduce that the analytical solution is of the form ($1/G^{0.5}$). This indicates that Mars vehicles are 62% more vulnerable to this type of overturn than Earth vehicles of similar geometry.

Tipping due to sideways motion is similar to tipping due to rotational impulse. Rather than an external triggering event, a change in vehicle orientation relative to its direction of movement causes a destabilizing moment due to the height of the center of gravity and thus the center of inertial forces, and traction of the vehicle's tires or treads on the ground. This can be countered by returning the vehicle to pointing in the direction of motion, if it is under control. Other than doing so, the tipping once started is likely to continue unless the vehicle stops moving prior to overturning. The coefficient of friction between the vehicle and the ground is unlikely to decrease, and in fact may increase as tires dig in or encounter heavy rocks or other obstructions. Tipping will start if overturning moment exceeds the moment that gravity and the vehicle width inherently provide:

$$Vy \times Hg \times Cf > G \times tw/2$$

Vy is the sideways velocity, Hg is the height of the center of gravity, and Cf is the applicable coefficient of friction (static or sliding) between the surface and the vehicle. tw is the width of the track, or distance between the tracks or wheels, and G is the local gravity.

As can be seen from the equation, reduced local gravity decreases the vehicle stability resisting overturn due to sideways motion, as it does with rotational impulse overturn. Vehicles on Mars will be roughly 2.63 times more likely to overturn due to dynamic upset or accidents than vehicles with similar configurations (height of center of gravity and width of track) on Earth.

In summary, Mars rovers are significantly more likely to overturn than Earth vehicles in several scenarios; 1.62 times as likely ($1/G^{0.5}$) due to impulsive overturning impacts or bounces, and 2.63 times as likely (1/G) due to skidding sideways. As the overall forces due to both impacts and bounces and due to sideways skids are proportional to the velocity squared, the relative safe speeds for geometrically comparable vehicles are 0.78 if concerned with impulsive overturns and 0.61 as fast if concerned with sideways skids. These are workable fractions, reducing safe speeds below earth analog conditions but not by an unreasonable amount. Proper training and vehicle design can compensate.

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6. MOTIVE POWER PRODUCTION

The power available to Mars rovers will likely be less than that available to Earth vehicles; lower speeds are acceptable, and tighter tradeoffs and technical problems lower performance. A number of prior works [Clark 96; Zubrin 92, 96] have argued effectively that required power cannot be provided by solar power systems. Nuclear reactors are too dangerous in close proximity with human crew, and RTG type power systems have very poor power to weight. We will therefore concentrate on chemically fueled rovers, utilizing internal combustion (piston or turbine), and fuel cell type power sources.

Internal Combustion

For internal combustion powered vehicles, if the motor and gearset are considered as a unit, power to weight ratios exceeding 1,000 W/kg are possible for short-duty lightweight motors. For rugged, high endurance, conventional motors, power to weight ratios are typically are much less than that: the Cummins VTA-903-T600 engine used in the M2 Bradley [Janes Upgrades 97] generates 493 kW and masses 1,190 kg. It is coupled with a 960 kg transmission. System mass is 2150 kg and specific power 230 W/kg. Gas turbines have specific power in the range of 1 to 6 kW/kg, but for vehicular applications gas turbines require significantly heavier transmissions (the M-1 tank requires a 1,960 kg transmission for 1,108 kW power). System specific power of gas turbine vehicle propulsion is 500 W/kg in the optimistic case, and can be worse. While substitution of aerospace materials and aggressive design and test can improve the specific power of internal combustion motor / transmission sets, there are practical limits to how far that process is likely to be able to go. We will assume that combustion based propulsion can generate 500 W/kg including the whole powertrain, though this may not be achievable in all cases.

Electrical Motors

For electrically powered vehicles, there are two segments to address, motors and power generation systems. For motors, industrial motor performance is 75 W/kg, with high performance lightweight motors around 150 W/kg. We will assume 150 W/kg motors can be rated to ground vehicle drive reliability requirements, but this assumption will need further test and justification.

Hydrogen Fuel Cells

Fuel cells providing electrical power can run at up to 200 to 300 W/kg, though most existing cells are lower performance. The Space Shuttle fuel cells are rated at 12 kWe continuous and 16 kWe peak performance and weigh 118 kg, a performance of 101 to 136 W/kg [Hamilton Standard 97]. Other references list specific power up to 370 W/kg [Fortescue & Stark 95] for other more modern fuel cell designs. These are hydrogen/oxygen fuel cells, which offer the greatest performance but low fuel density: conversion efficiency in these cells is 70% or greater from chemical energy to electrical output energy, with some high performance cells with topping cycle thermal turbines operating at 85%. We will assume 300 W/kg and 70% efficient.

Hydrocarbon Fuel Cells

Fuel cells using hydrocarbon reactants such as methanol or methane, either directly or pre-cracking into hydrogen also exist, but at lower specific efficiency and somewhat lower power. Current power figures for these cells appear to range up to 430 W/kg [Ballard 98]; details are hard to determine, though, as most of the programs are aimed at methanol or gasoline fuel cell cars, which have significant commercial potential and most details are being closely guarded. Some information is available on some cells; low power direct-methanol cells for non-auto applications [DTI 97] being developed now are working at 60 W/kg and 36% efficiency, though 45% efficiency is expected shortly. We will assume 400 W/kg and 40% efficiency though better may be available and announced reasonably shortly. We will also assume that the proton-exchange direct methanol cells can run on methane with no performance degradation, though this needs detailed analysis and test to verify.

Combining these into an integrated power system, we get the following projected system performance figures:

For hydrogen/oxygen fuel cells, power system specific mass of 100 W/kg at 70% efficiency is well justified at the current state of the art.

For methanol/oxygen fuel cells power system specific mass of 110 W/kg is reasonable with 40% efficiency.

7. FUEL CHOICES

The fuel consumption rate of an ideal power system is the useful power produced divided by a system efficiency and the energy content of the fuel.

The most promising fuel and oxidizer combination for Mars surface operations appears to be methane and oxygen; both are storable, easily produced with a little bring-along hydrogen, and well known. Methane can be used in fuel cells and internal combustion engines quite flexibly. The combination has 2,800 W-hr/kg specific power density.

Alternatively, we can consider hydrogen/oxygen fuel cells at 3,750 W-hk/kg, though much lower fuel density (1,312 W-hr/l versus 2,380 W-hr/l for methane/oxygen).

As was discussed in the previous section, hydrogen/oxygen cells can run at over 70% efficiency, and the best projected methane/oxygen cells at 45%.

Internal combustion engines have significantly lower overall efficiencies. Any combustive engine is a heat engine, in thermodynamic terms, and is first and foremost subject to the Carnot equation describing maximum efficiency for heat engines, $E = (Th - Tc) / Th$. No heat engine may exceed the Carnot efficiency, and typical overall values for practical engines are generally only 0.25 to 0.35.

8. SAMPLE VEHICLES

For purposes of demonstration, we will present some sample rover designs utilizing various propulsive options as described above. The following rover concepts are not intended as baseline vehicles for any particular mission; particularly, they are larger and more capable than needed by most proposed missions. These samples are done to be easy to analyze and compare. Actual rovers of half the proposed size or less are more likely; I picked 10 tons as a round number.

We will consider three sample 10 ton rovers: one that is internal combustion engine powered, one that is hydrogen fuel cell powered, and one that is methane fuel cell powered.

Power Requirement

Existing earth offroad vehicles have power to weight ratios of roughly 20 hp/ton (15 kW/t). We will use the equivalent rating at Mars.

Suspension

Designed for earth gravity, both vehicles would require about 1000 kg worth of tires and suspension. As they will be operating under 0.38 G Martian gravity, this is reduced to 380 kg (400 kg) each.

Motive Power

The target power to weight ratio equivalent is 20 hp/ton, or 15 kW/ton. We earlier argue that for Mars missions this should be multiplied by local gravity, so the desired power is 15×0.38 or 5.7 kW/t, or 57 kW total.

Our internal combustion vehicle with estimated power system specific mass of 500 W/kg will require 115 kg of motor and transmission.

The hydrogen fuel cell vehicle will require 570 kg of fuel cell and electric motors if the 100 W/kg specific power density is assumed.

The methane fuel cell vehicle will require 520 kg of powerplant and drive at 110 W/kg.

Mass Budgets

If we assume that both vehicles have a 500 kg structural frame on which other components are mounted, the total vehicle frame, suspension, and drivetrain systems are:

1,015 kg for internal combustion
1,450 kg for hydrogen fuel cells

1,400 kg for methane fuel cells.

We will assume this rover is designed to accommodate 4 persons for up to a month, requiring 100 m^3 of volume (a 4 m diameter cylinder 10 m long) massing about 2,000 kg and with 2,000 kg of life support and other equipment and 750 kg of expendables. Total mission payload is thus 4,750 kg. Remaining payload for the three sample vehicles are:

4,235 kg for internal combustion,
3,800 kg for hydrogen fuel cells, and

3,850 kg for methane fuel cells.

If we assume that fuel tankage mass is 75 kg/m^3, then allocating the entire remaining mass for fuel and tanks gives us useful fuel of:

4.63 m^3 (3.85 t) for IC
7.78 m^3 (3.22 t) for hydrogen fuel cell

4.21 m^3 (3.50 t) for methane fuel cell

Basic Range and Performance

For a simplistic range estimate, we will divide the total fuel by 30 and assume 8 hours a day are spent driving.

The IC engine consumes 16.0 kg/hr. the hydrogen fuel cell 13.4 kg/hr, and the methane fuel cell 14.6 kg/hr. At their system efficiencies of 0.30, 0.70, and 0.40 respectively and fuel power densities of 2.80, 3.75, and 2.80 kW-Hr/kg of chemical energy, the system average output power values are:

13.44 kW for the IC engine
35.18 kW for the hydrogen fuel cell system

16.33 kW for the methane fuel cell system

Using these average output power levels, we can derive average speeds. The rovers mass 10,000 kg loaded and weigh 380,000 N each, equivalent at earth to 3.8 tons mass. The equivalent average active power to weight ratio is therefore:

3.5 kW/ton for the IC engine
9.26 kW/ton for the hydrogen fuel cell system

4.30 kW/ton for the methane fuel cell system

Recalling that the formula for road speed is v = sqrt (p/w) × 24.7 for wheeled vehicles, we get average speeds of:

46.2 kph for the IC engine
75.1 kph for the hydrogen fuel cell system

51.2 kph for the methane fuel cell system

If the equivalent cross country speed is half of the road speed, which is a normal assumption for earth vehicles, then the three Mars rovers can be expected to actually move at around 23 kph, 37 kph, and 26 kph respectively. Among other considerations, faster speeds may risk suspension and tire damage due to rock impacts. Over their 30 day endurance, this gives ranges of:

5,520 km for the IC engine rover
8,880 km for the hydrogen fuel cell system

6,240 km for the methane fuel cell system

If increasing performance as fuel is burned off is taken into account, the range increases proportionally.

Range with Hotel Loads

If the propulsive power must also power the life support and other electronics systems, then range decreases proportionally. Let us assume that the hotel power load for the rover is 3 kW. This corresponds to fuel consumption of:

IC engine: 3.57 kg/hr, 85.7 kg/day
H2/O2 FC: 1.14 kg/hr, 27.4 kg/day

Me/O2 FC: 2.68 kg/hr, 64.3 kg/day

If the vehicle is driven 12 hrs/day at an average actual power load of 0.25 peak (57 × 0.25 or 14.25 kW), then rover speed will average 24 kph using the 0.5 assumed multiplier for offroad travel, daily movement will average 288 km, and propulsive fuel use will be:

IC engine: 205 kg/day
H2/O2 FC: 65 kg/day

Me/O2 FC: 153 kg/day

Combined usage is:

IC engine: 291 kg/day
H_2/O_2 FC: 93 kg/day

Me/O_2 FC: 218 kg/day

0-margin endurance will be:

IC engine: 13.23 days
H_2/O_2 FC: 34.6 days

Me/O_2 FC: 16.05 days

This gives effective straight line distances of:

IC engine: 3,810 km
H_2/O_2 FC: 9,965 km

Me/O_2 FC: 4,622 km

In this case, the hydrogen/oxygen fuel cell vehicle shows more than a factor of two advantage in range and endurance over the competitive vehicles, and the methane/oxygen fuel cell has 21% range advantage over the internal combustion engine vehicle.

9. CONCLUSIONS

A number of conclusions spring from this research into Mars rover design.

Stability dictates vehicle configuration, and the reduced stability of Mars rovers will dictate that they be designed to be lower to the ground than Earth vehicles, not taller. Most detail designs for large Mars rovers have assumed a large cylindrical pressure hull that had considerable ground clearance. It is better to go low, oval pressure hull and lower ground clearance (earth off road vehicles get by with 0.5 meter, Mars probably can too, but rock size distribution and vehicle belly structural strengths need to be appropriately considered). This may be inconvenient in packaging for transport to Mars. Nobody said this was going to be easy.

The impact of surface rocks on rover operations and speed is significant: rocks of the right sizes to significantly damage rovers are plentiful near all lander sites and probably are present in lesser but still significant quantities over most of the Mars surface, particularly some of the more interesting traverse targets. The detailed impact on design and operations is not yet known, but may significantly decrease safe operating speeds below commonly considered values and increase maintenance and vehicle damage risks.

The best fuel combination, despite the low density, is hydrogen/oxygen fuel cells and electric motors for the powertrain. This gives at least 50% better range than competing systems. If large quantities of hydrogen are not available, or its storage proves to be overly difficult, then use of methane/oxygen internal combustion or fuel cell systems are roughly comparable in terms of rover performance, though the fuel cell vehicles enjoy an advantage of about 22% better range per fuel mass consumed and thus reduce consumables and ISRU loads.

Finally, there are literally hundreds of large, high performance off road vehicles available on Earth for comparison and analysis purposes, and with due attention to the scaling factors and areas of difference, much can be learned in detail design, configuration, and other areas from these many examples.

10. DIRECTIONS FOR RESEARCH

A number of areas in which research is needed for further progress exist.

Surface Detail Investigation

A greater level of understanding of the detail surface characteristics of Mars is required for rover design. Of particular interest are:

- soil characteristics and rock size distributions over the relevant areas of the surface that surface traverse expeditions are likely to cover.
- topology details such as slopes, gully widths, small and mid-scale surface disruptions.

At first analysis, we need the ability to count size distributions of 10 cm and larger rocks as input into rover detail design. We have total surface rock coverage percentage already from thermal data, but the size distribution from 10cm up is critical as the apparent distribution corresponds exactly with sizes likely to damage rover suspensions. Determining such distributions near landers is trivial, but hard from orbit, that resolution being roughly the same as achievable by Earth orbiting US military visual imaging satellites. While low weight optics and narrow swaths of view should be acceptable, it is still a difficult proposition. It may be necessary to fly a small field of view high resolution visual imaging camera, with 10cm or greater resolution, on a future orbiter to resolve the question.

Methane Fuel Cell Performance Determination

Methane is an attractive fuel on Mars, but not being examined for earth based fuel cell applications, losing out to methanol, gasoline, and hydrogen for a number of reasons. The chemistry of proton-exchange direct reactant methanol fuel cells appears to the author to be usable with methane as well. This assumption needs further analysis and practical testing.

Mechanics of Vehicle Maintenance in EVA Suits

A key question in designing rovers is what level of external repair and maintenance will be performable given the mobility and dexterity limits imposed by EVA suits. It is too much to hope that rovers on long traverses will be 100% reliable, thus rover design must follow experimental validation of what repairs will be possible in the field in suits. It is possible that repair of thrown or broken track-type suspensions will be impossible or impractical in EVA gear, in which case only wheeled rovers should be planned.

This question can be answered in some detail using fairly inexpensive testing. Using simulated EVA suits, pressurized but obviously not requiring actual full closed loop life support, we can have experienced vehicle crewmen of appropriately scaled wheeled and tracked vehicles perform various field maintenance procedures, recording the results for analysis. The test EVA suit simulators merely have to replicate dexterity and mobility limits with moderate to high fidelity, and this should be relatively inexpensive to develop and validate.

The tests should include replacement of tires, suspension elements, replacing thrown or damaged tracks, and recovering vehicles stuck in sand and/or other soil types which mire the vehicle.

Dynamics of Motion, Drag, and Power at Fractional Gravity

A detailed theoretical look at the influence of gravitational force on vehicle motion at the macroscale (not just light rovers) is required. Once that has been performed, then experimental verification, perhaps using testbeds with sub-scale driving tracks flown on fractional gravity parabolic arc test aircraft, should be performed to validate the detailed theory.

11. APPENDIX: EARTH VEHICLE DATA

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