

EXPLORATION MOBILITY WITHIN DRIVEBACK CONSTRAINTS: THE CASE OF MERIDIANI PLANUM, 2019

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Introduction. Contemporary Mars surface operations planning typically distinguishes between two types of exploratory vehicles: unpressurised rovers (a small, unenclosed Apollo LRV-like vehicle able to extend the life support duration of explorers in spacesuits with a range of up to 500km) and pressurised rovers (a larger vehicle capable of supporting explorers in a shirt-sleeves environment for days at a time for distances of 500-1000km) [1,2]. It is usually convenient to classify exploratory sorties in terms of range from landing site habitat, duration and/or vehicles required. Short range sorties would be conducted on foot to range over a range of about 10km. Medium range explorations would be conducted over a range of up to about 200km using an unpressurised rover. Longer range sorties would require a pressurised rover.

Whether on foot or by vehicle, planning for any safe Martian exploratory activity will need to achieve a complex balance of factors such as:

- the value of the exploratory target site
- the life support consumables available
- the capabilities of the vehicle
- the available daylight hours
- the terrain the expedition must traverse

The balance is complex because the factors themselves are not simple (e.g. the capabilities of a vehicle may include range, speed, climbing ability, maximum payload etc.) and the variables interact in complex ways (e.g. available life support consumables vary depending on mission and vehicle type, and may be affected by terrain). It will be argued here that given a specific travel risk policy, and given some capacities expected to be available to rovers circa 2019, the maximum radii of medium and long range exploratory circles - and thus the possible sites which might be visited at the Meridiani site - should both be constrained by a single factor: the average maximum safe speed at which an unpressurised rover may be driven over unexplored territory during daylight hours. This will be shown to hold whether the exploration is being conducted by unpressurised rover, or by pressurised rover. A new sortie planning method guaranteeing that a putative mission

sequence is both feasible and safe within these constraints is proposed. The method is also applicable to short-range exploration near the base without vehicles, when the crucial factor is average walking speed in daylight hours.

Capacity of Rover Vehicles: 2005 and 2019

There are good reasons to design Mars rovers around a fuel cells which power electric motors at each wheel via an electronic transmission [3]. Such vehicles can be simpler, less massive, more controllable and more reliable than other, more familiar vehicular drive trains. Although fuel cell powered vehicles are not likely to compete with hybrid petrol-electric power plants in Earthbound automobiles in the next two decades, the reasons for this have more to do with the economics of mass production and the legacy of a distribution system designed to deliver fossil fuels than with any deficiency of fuel cells as a power plant. These factors do not apply to highly specialised exploration vehicles. According to a 2003 MIT report, with normal development of fuel cell vehicles we may expect improvements in energy consumption of 52% -65% [4]. (These figures probably underestimate the value for a Mars rover, since they include total energy over the lifetime of the vehicle, including manufacture - again, not applicable in the case of vehicle which is not mass-produced). Furthermore, the mass, cost and low-temperature performance of fuel cells are all rapidly improving [5].

A contemporary vehicle of about the size and mass of the putative unpressurised rover is the 1,760kg 80kWe Honda FCX, capable of carrying 4 persons for about 257km between refills [6]. The fuel for this vehicle is hydrogen gas, which would probably not be available in quantity from in-situ resource production, at least for the first missions. Nevertheless, taking into account the mostly flat landscape of Meridiani Planum, the lower gravity and the lower payload requirements, it seems reasonable to expect that this target could be reached or exceeded in a less massive, lower powered rover using a fuel available from in-situ resources on the by 2019. We should also expect equivalent improvements in the performance of the larger, pressurised rover. Today, 190KWe fuel cell passenger buses under test in cities in Europe, Australia, China and the United States can carry up to 70 persons about 200km between refills [7].

Again, given the rate of improvement of fuel cells and associated vehicle technology, it seems reasonable to expect a better performance from a pressurised vehicle, the payload for which would be far less than in a commercial bus.

Daylight driving risk policy

Assuming an unpressurised rover could sustain an average safe travel speed V_{ur} of 30 km/h, and that the EVA suits of 2019 can support life for 10 hours, the maximum theoretical safe radius of exploration appears to be 300 km. However, this oversimplifies the reality, since i) reserves of consumables could be drawn from the unpressurised rover and ii) travel at night would probably be considered too risky in an unpressurised rover, due to the cold and reduced visibility, in all but the gravest emergencies. So given a fully provisioned unpressurised rover which could extend life-support of the crew (say, to 16 hours), the maximum radius is actually more likely to be limited by the available daylight hours. At an equatorial region such as Meridiani Planum this is roughly 12.25 hours in all seasons [8], during which time the unpressurised rover could theoretically be driven back a maximum of 367.5 km.

Geometrical sortie planning method

To describe the constraints and lay the groundwork for the geometrical sortie planning method, we begin by considering the case of medium range sorties. Later, the idea will be extended for long and short range sorties. Given the policy of driveback in daylight only, there will be a medium-range exploration circle of safety around any landing site on Mars with its radius set by the amount of daylight remaining and the speed of the unpressurised rover. Explorers must stay within this circle at all times to be able to reach the habitat before nightfall. Moreover, this circle shrinks steadily as the daylight hours are consumed. This relationship can be expressed as:

$$(T_d - T_e) - \frac{R_s}{V_{ur}} = 0$$

where T_d is total daylight hours

T_e is elapsed hours (hours since dawn)

V_{ur} is the permitted average driveback speed limit of unpressurised rover

R_s is the maximum safe range

Now given an average driveback speed limit (again set by practical safety considerations rather than rover capabilities), it is possible to calculate a maximum safe range for any time of the day, or conversely for a given range calculate the latest departure time for safe return:

$$T_e = T_d - \frac{R_s}{V_{ur}}$$

Remaining with a T_d of 12.25 hours and a V_{ur} of 30kph, we are then able to express the safety constraint at Meridiani as a graph (see Figure 1).

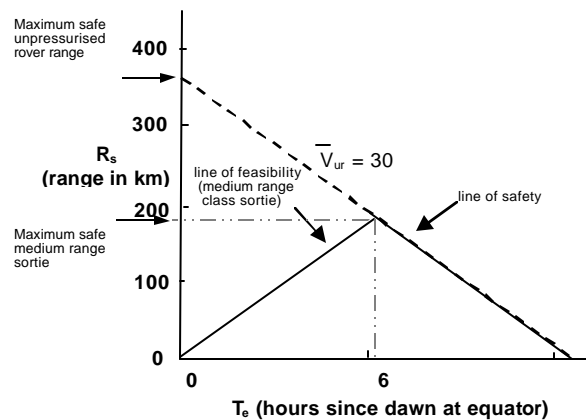


Fig 1. Constraints on a medium range sortie at Meridiani Planum

The line of safety represents the maximum allowable safe distance from base at any time during daylight hours. At dawn an unpressurised rover could be at a maximum of 367.5km from the base; by dusk it must have reduced this to zero. But for medium range sorties, not all positions on the line are feasible, because the rover must depart the base no earlier than dawn. Therefore a line of feasibility is added which forms a triangle centred on the local noon, which represents the furthest the rover can traverse and still return safely (183.75km). All medium range sorties must be conducted at points under the area formed by this safety triangle.

The earliest time a rover could reach a target at a given range may be read off the line of feasibility; the latest time it may remain there is read off the line of safety. A safety margin of say 5% may be added to the diagram by shifting the apex of the safety triangle 0.6125 hours to the left but maintaining the dawn and dusk crossing points at zero range. This has the effect of making all

departure and arrival times away from the base slightly earlier, which protects against small unexpected delays (Figure 2).

Usually sorties would include one or more stops of various durations at the target for exploratory work. A single stop must fit within the triangle of safety truncated horizontally by the range. In a sortie with multiple stops, the alternating sequence of bands representing drive and stop operations must be arranged left to right so that they all fit within the available time/range limits. Since the most distant targets are generally the most constrained, sortie planning should begin with those.

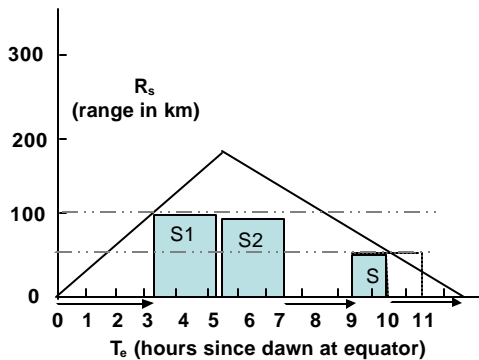


Fig 2. A feasible and safe sortie with a 5% safety margin.

Figure 2 shows a feasible and safe medium range sortie, which originates at a habitat placed near the geometric centre of Opportunity's landing ellipse at 5.0° W and 2.0° S. The sites to be visited are

- 1) rim of a large filled double crater on the western boarder of the P2 middle plains of Terra Meridiani 100 km north west
- 2) small hematite "island" outside of main local deposition boundary 98km to the northwest
- 3) north rim of an large undivided crater at the southern limit of the P2 middle plains 50km south-southwest.

A stop of two hours is proposed for each site. Moving from left to right and beginning with the furthest site (double crater), and assuming the rover can leave at first light, the horizontal 100km line intersects with the line of feasibility at 3.3hrs. This is the arrival time at Site 1. The rectangle representing the proposed 2-hour du-

ration at this range falls entirely within the safety triangle, and so is permitted. Next a short traverse of 2km (3.9 minutes) is measured off, marking the arrival time at Site 2. The two hour rectangle at the 98km range still fits beneath the safety rectangle. Next comes a third traverse of 100km to Site 3, at which the 50km horizontal line intersects the line of safety at approximately the 9.5 hour mark.

Now however, we encounter a problem: the 2-hour rectangle representing the stop cannot fit beneath the line of safety. However, if the S3 duration was reduced to 1.5 hours, it would be safe, so that solution is plotted. Alternatively, if 2 hours at Site 3 was required, the duration of S1 and/or S2 could be reduced to allow more time at S3.

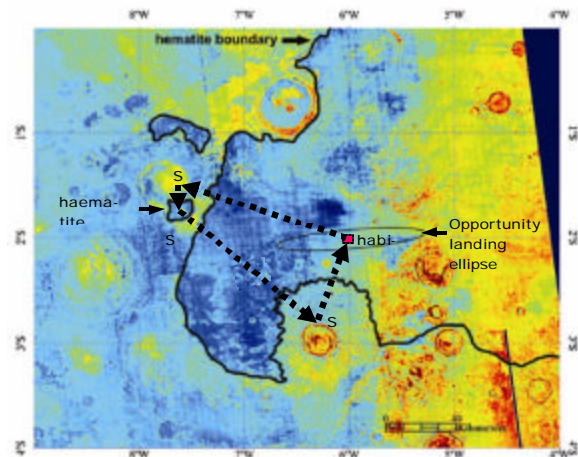


Fig 3. The plotted path of the medium range sortie. (map from Hynek, et.al., 2004 [8])

Long range sorties are also constrained by the unpressurised rover driveback, but can reach target sites at greater ranges if we assume that the pressurised rover will carry the smaller unpressurised rover with it, perhaps folded up on the roof, just as the Apollo LRV was folded into a package small and light enough to be carries on a Grumman LEM [9]. Here we also stipulate that in the event of an accident it will still be possible to stay at the accident site overnight, either using the (immobilised) pressurised rover or else camping in an emergency inflatable shelter. The overnight stay allows for a departure at or near dawn. Under these conditions, the area of safety becomes the larger triangle in Figure 1, thus providing the maximum safe driveback of about 348 km, allowing for a 5% margin, which stays

constant regardless of when the pressurised rover accident occurs.

In years beyond the first explorations, when a second or third pressurised rover could be delivered, the full range of these long duration vehicles would become safely available. There would be a way to extend this limited range for a first mission if necessary, however. The pressurised rover to tow a detachable trailer containing consumables for life support, an inflatable shelter and power. This would be left at a points along the outbound route corresponding to the safe driveback circle set by available daylight hours, where it could serve as overnight camping stop for a crew driveback in an unpressurised rover. The trailer could also serve the same function for a rescue crew coming from the habitat to aid the stranded sortie team. The trailer would be picked up during the return leg of the journey for reuse. Such a portable life-support trailer could also have other uses in emergencies, as so are consistent with the design philosophy of multi-use technologies.

The geometric method of feasible, safe sortie planning applies for short range explorations on foot. Here, the crucial factor is average safe walking velocity in an EVA suit, which might be conservatively estimated to be 2km/hr, which sets the maximum feasible, safe radius to 12.25km. Note that short-range safety circles of this radius may also be centred on the pressurised rover during long duration missions, where the pressurised rover becomes the safe haven after dark.

References: [1] Hoffmann, S.J. and Kaplan, D.I. (Ed.s) (1997) *Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Study Team*. NASA Special Publication 6107. 3/105-110. [2] French, J.R. (1987) An Overview of Mars Surface Mobility Justification and Options. In Stoker, C. (Ed) *The Case for Mars III*, American Astronautical Society Vol 74, 1987, 619-632. [3] Mann, G.A. (2002) Design, Construction and Operations Plan for the Starchaser Marsupial Rover. *Proc. 2nd Australian Mars Exploration Conference, University of Sydney, July 2002*. [4] Weiss, M.A., Heywood, J.B., Schafer, A. and Natarajan, V.K.. (2003) Comparative Assessment of Fuel Cell Cars. LFEE 2003-001 RP, Massachusetts Institute of Technology. [5] Honda Motor Company, Ltd.. Honda HCX Technical Specifications. Available at <http://world.honda.com/FuelCell/FCX/specifications/> [6] Ashely, S. (2005) On the Road to Fuel Cell Cars. *Scientific American*, 292,3, 50-57. [6] Ballard Power Systems, Inc. (2004) Fuel Cell Bus Info Sheet. At http://www.ballard.com/rsources/transportation/Fuel_C

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