Review of Mars Rover Wheel Design and Mobility Performance on Slopes and Regolith

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The advancements of Mars rover wheel designs have been crucial to improving mobility on the Red Planet's challenging physical environmental conditions. Early missions revealed repeating issues with wheel traction, durability, and wear when traveling on loose regolith, sharp rocks, and slopes under reduced gravity. These challenges pose a critical risk to mission success since wheel failure or excessive degradation constrain rover range, mission duration, and achievable scientific data. Current Mars rovers tackle these issues through aluminum wheels with grousers, refined geometries, and combination with rocker-bogie suspension systems; however, data from past missions such as *Spirit, Curiosity* and *Perseverance* showcase that wheel damage and mobility restrictions remain in rough terrain. The purpose of this paper is to systematically review the progression of Mars rover wheel designs, looking at the engineering motives behind material selection, wheel geometry, and grip structures, as well as the advantages and limitations experienced throughout successive missions. This review synthesizes experimental results, mission data, and terramechanics studies to identify recurring design trade-offs and unresolved issues. The hypothesis of this study is that many wheel-related challenges result from frequent compromises between mass, durability, and traction, and that reviewing past designs can disclose underused methods. Alternative approaches, including use of compliant materials and adaptive wheel concepts, are discussed alongside the reasons that have not yet been completely implemented. Ultimately, the paper aims to serve as a centralized reference that allows future researchers to avoid repeated design defects and more efficiently develop wheel systems for next-generation Mars rovers.

I. Introduction

Exploration of the Martian surface has heavily utilized rovers to conduct scientific studies in areas inaccessible to humans [1, 2]. Despite significant advancements in autonomous navigation, instrumentation, and power systems, rover mobility on the planet's unique surface remains a critical limitation in completing missions successfully [3]. One of the biggest challenges that rovers face come from soft terrain which causes a combination of high slip and sinkage due to loss of traction [4, 5, 6]. Unlike vehicles used on Earth, Mars rovers must account for payload mass constraints, limited possibility for repairs, and long exposure to abrasive terrain when designing for mobility.

Under these extreme constraints, wheel design becomes a point of vulnerability and wheel-related issues have been recorded in nearly every Mars rover mission [5]. For example, *Spirit* and *Opportunity,* the Mars Exploration Rovers (MER) launched in 2003, struggled with loss of traction and high slip ratios because of soft soils in areas like Troy around the Gusev crater [7]. It was in this type of terrain, where *Spirit* was found stuck for many months and eventually failed to get out [5]. Issues were also seen on Mars Science Laboratory's rover *Curiosity* which encountered unanticipated puncturing and tearing of wheels because of sharp rocks at Gale Crater on sol –

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Martian solar day – 490 out of a 668 sol original mission duration [8]. These repetitive problems demonstrate the significance of wheel design as a crucial subsystem rather than a secondary mechanical part.

As mission duration on Mars becomes longer and targets increasingly complicated terrain, a comprehensive review of previous wheel designs and their performance is necessary. By studying the engineering rationale behind decisions on design and analyzing their consequences, this work seeks to supply future rover designers with a centralized source that reduces repetitiveness of design flaws and supports development of the newer rovers.

II. Terramechanics and Martian Surface Interaction

The surface of mars applies unique and often clashing constraints on the design of a rover wheel. Terramechanics – the study of wheel-soil interaction mechanics – can be used to traverse over fine dust, loosely compacted soil, and hidden rocks. Experimental studies in planetary soil mechanics [1] show that wheel performance relies heavily on normal load distribution, wheel width-to-diameter proportion, soil cohesion, and grouser – metal ribs that span the width of the exterior of the wheel to improve traction – height and spacing. With lower gravity (0.38g) comes a decrease in normal force, reducing available traction while concurrently diminishing resistance to sinkage. Although increasing wheel diameter would improve traversing over obstacles, it would require adding to the overall mass structural stress.

Repeated studies that look at simulations of rover mobility [2, 5] verify that too much wheel slip not only decreases efficiency but causes faster structural damage and increases energy usage – a large limitation for solar-powered rovers.

III. History of Martian Rover Wheel Design

A. *Sojourner*

The first Mars rover to be successfully deployed was *Sojourner* on the Mars Pathfinder mission in 1997. This rover used six small aluminum wheels with a diameter of about 13 cm [3]. The wheels had shallow cleats that improved traction on looser soil as well as a rocker-bogie-like suspension system.

An informative experiment aboard *Sojourner* was the Wheel Abrasion Experiment [9] which observed damage caused by Martian dust. Engineers used small strips of aluminum, nickel, and platinum that were attached to the rover to measure degradation by reflectance. The results of the experiment showed that there was considerable wear on parts made of aluminum, especially on thinner sections. It was also verified that Martian regolith is abrasive to mechanical parts and able to progressive damage materials.

Due to the mission being designed for a short seven sols, wheel durability was not of high importance compared to basic mobility and simplicity [9]. Even with these limitations, *Sojourner* contributed to important validation of concepts on Martian rover mobility and wheel-soil interactions.

B. *Spirit* and *Opportunity*

Adding to the success of Pathfinder, the MERs – *Spirit* and *Opportunity* – incorporated notably larger wheels, approximately 25 cm in diameter, made of aluminum joined with grousers that improved traction [10]. Also using a rocker-bogie suspension system for these two rovers allowed for climbing over obstacles that are about the same size as the wheel diameter - improving accessibility to new areas [7, 1]. The design's emphasis was on structural rigidity and reduced mass, showcasing the engineering decisions that aimed to maximise reliability.

By sol 1899, some shortcomings were revealed. *Spirit* was found to be immobilized by soft, sulfate-rich soil after struggling with extreme wheel sinkage that surpassed predictions [4, 7]. This event brought to light the limitations of both adaptability from wheels and the accuracy of predictions from pre-mission terramechanics models. Even with *Opportunity* avoiding a similar entrapment, both rovers suffered from mobility constraints which underscore the necessity of further understanding of wheel-terrain interactions.

C. ***Curiosity***

The *Curiosity* rover from the Mars Science Laboratory was a step toward larger-scale rovers and what they could accomplish. To account for the increased mass, *Curiosity* used aluminum wheels of 40 cm in width and 50 cm in diameter which would help reduce sinkage and provide the ability to clear more obstacles [8]. To be as efficient as possible with mass, engineers designed the wheels to have thin aluminum skins strengthened with many grousers.

Even though this design provided more range of mobility on Martian terrain, early operations showed unexpected issues in durability. In fact, within the first couple hundred out of the expected 669 sols, *Curiosity's* wheel skins were already showing evidence of puncturing and tearing from the rocks at Gale Crater [8, 11]. After a detailed analysis, it was found that high localized stress on the tips of the grousers combined with not enough skin thickness caused the damage visible in Fig. 1. After learning of this, mission planners had to find alternative routes and identify new driving strategies, demonstrating how flaws in wheel design can directly limit mission operations and jeopardize mission success.

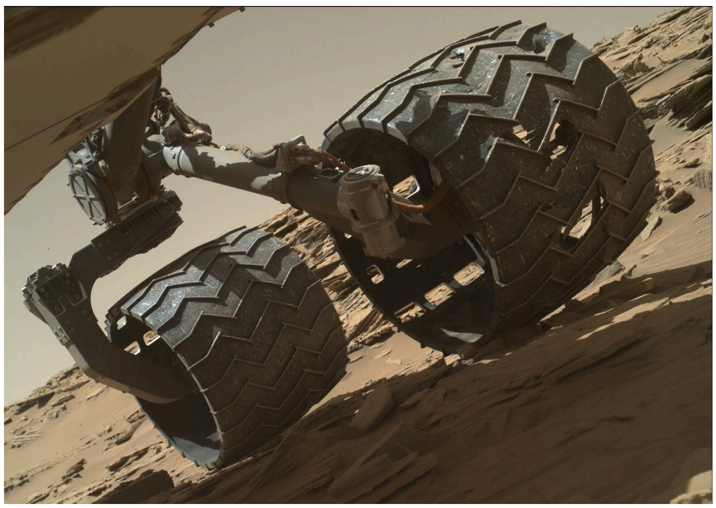

Fig. 1 Inspection image of Curiosity's wheels showing punctures and wear caused by sharp terrain features during Martian surface operations. (NASA/JPL-Caltech, public domain)

D. ***Perseverance***

The latest Martian rover *Perseverance* was designed to overcome the challenges that *Curiosity* faced. Major changes like increased skin thickness, grouser count reduction, and refinement of wheel geometry to better distribute contact stresses were added [2]. Specifically, the skin thickness was doubled from that of *Curiosity* and the width was reduced by one-third to maintain wheel mass [4]. To account for the reduction of width, the wheel diameter also increased to 52 cm, ensuring tractive capabilities [4]. These updates focused on improving durability without comprising mass margins. Current data shows enhanced resistance to damage; however, performance for longer durations is an ongoing assessment.

IV. Design Trade-Offs

The evolution of Mars rover wheel designs displays continuous trade-offs between mass, durability, and traction. Rigid aluminum wheels are a top choice of material due to its simplicity, ease of manufacturing, and structural efficiency, yet they were found to be easily abrazed and fatigued when used on rocky terrain [4, 9]. As shown in Fig. 2, increasing wheel diameters was also preferred and was the trend seen as new rovers were designed. Choosing larger wheels lessened contact stresses and sinkage but did, however, add to the mass and caused complications with remaining under launch vehicle constraints. Another trade-off seen in these rovers is grouser size. While higher grousers improve grip, they increase the chance for sinkage and disrupt the surrounding regolith. Similarly, choosing a rigid wheel design allows for simplicity but also transfers shock loads to the chassis. A compliant wheel design would absorb any impact but would require complexity and risk assessment. These compromises show support for the hypothesis that wheel-based mobility failures are not independent design errors, but predictable consequences of balancing engineering mass constraints.

Fig. 2 Isometric comparison of Mars rover wheel sizes. Sojourner (center), Spirit/Opportunity (left), and Curiosity (right), illustrating the progression toward larger wheels across missions. (NASA/JPL-Caltech, public domain)

V. Alternative and Underutilized Concepts

Various alternative wheel strategies have been reviewed but not yet applied to missions. Some include compliant mesh wheels, shape memory alloy adaptive wheels [9], manufactured lattice structure, and hybrid rigid-flexible wheel systems. A good example of these is the spring tire concept that was created in terrestrial testing conditions, which showcased large amounts of deformation tolerance without lasting damages. Even with promising results, concerns on dust infiltration, fatigue, and integration complexity are still present.

In terms of alternative materials, titanium alloys or composite materials for skins have been proposed. Costs and manufacturability, however, limit the implementation of new materials.

VI. Discussion and Future Prospects

The repeated experience of wheel limitations affecting rover mobility across Mars missions supports the hypothesis that compromises between mass, durability, and traction cause major challenges. Even after progressive improvements, modern wheel designs continue to struggle with similar failures observed in prior missions, particularly when traveling over sharp or loose terrain.

Future mobility systems on rovers will benefit from improvements in materials engineering and refined use of terramechanics data collected from field operations. Using on-site measurements more comprehensively could also advance guidelines for wheel designs and reduce uncertainty in calculating predictions. Ultimately, leveraging former lessons in a centralized means is the way that future Mars rovers reach longer life-spans, minimize operational constraints, and amplify scientific return.

Table 1 summarizes fundamental design features and resulting performance for Mars rover wheel systems, emphasizing both effective strategies and recurring challenges.

Table 1. Summary of Mars Rover Wheel Design Evolution

Rover	Wheel Diameter (cm)	Material	Lifespan	Key Design Features	Observed Issues
Sojourner (11.5 kg)	~13	Aluminum	83 sols (*7 sols)	Cleated rigid wheels	Limited durability data
Spirit/Opportunity (185 kg)	~25	Aluminum	2,208 sols/ 5,111 sols (*90 sols)	Grousers, rocker-bogie	Sinkage, entrapment
Curiosity (899 kg)	~50	Aluminum	4,800 sols (*688 sols)	Thin skin, many grousers	Early punctures, fatigue
Perseverance (1,025 kg)	~52	Aluminum	*688 sols	Thicker skin, fewer grousers	Reduced but ongoing wear

* expected lifespan

Future missions that aim to tackle steeper slopes and longer travel times will likely require improvement of materials, refined geometries, and upgraded modeling to allow long-term mobility.

VII. Conclusion

Mars rover wheel design has advanced significantly over the past decades, influenced by experience in operating and growing engineering capabilities. From supporting 11.5 kg rovers over 80 sols to propelling large 1 ton rovers over 4,000 sols, increasing wheel diameter and using innovative geometries has proven successful. Despite these changes, mobility issues relating to wheels remain a restricting element as they are a direct lead to possible mission termination. This paper reviewed the evolution of Mars rover wheel design, examined the engineering decisions behind key changes, and identified repeating concerns observed on missions. Based on these findings, future designs of rover wheels should prioritize hybrid architectures that redistribute stress, reduce plastic deformation, and adapt better to the heterogeneous Martian terrain. Additionally, incorporating advanced materials with improved fatigue resistance or modular load-distributing geometers would be more sustainable than just changing wheel thickness. Because mass will continue to be a constraint in planetary missions, reallocating structural mass towards damage-tolerant systems rather than damage-resistant systems would also prove more effective in long-term mobility.

By consolidating lessons learned and underlining newer alternatives, this work provides a centralized reference that can lead rover designers to developing more robust mobility systems, ultimately allowing increased scientific productivity when exploring the Martian surface.

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