Broader Interests and Applications
The view of a JPL Hardware Engineer

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MER Flight Vehicle, ‘Spirit’, during Integration & Test
MER Mobility Design

- The Rocker-Bogie mobility suspension is comprised of 6 driven wheels, with the outer 4 wheels steerable.

- The Rocker-Bogie suspension utilizes a differential and linkages to effectively equilibrate the wheel loads during drives.

- The first rover to Mars, Sojourner, also utilized a rocker bogie suspension.

The rover Spirit shown behind Marie Curie from the Mars Pathfinder mission.
MER Mobility Requirements

- Last 90 “sols” on Mars
- Drive up to 1 km
- Traverse obstacles up to 25 cm in height
- Traverse over very soft soils
- Be statically stable while tilted in any direction up to 45 degrees
- Not be “torque limited”,
- Perform precision drives to science targets
- Wheels designed to achieve a low engineering ground pressure on soft terrain

View from the rover *Opportunity* of the Burns Cliff formation, Endurance crater
Rover and Wheel Properties

**Curiosity (Mars Science Laboratory)**
- Mass = 960 kg (current best estimate)
- Rover Weight on Mars = 3572 N
- Average Weight per Wheel = 595.3 N
- Wheel Center Diameter = 0.500 m (with cleats)
- Wheel Outer Diameter = 0.465 m (with cleats)
- Wheel Width = 0.400 m

**Spirit and Opportunity (MER)**
- Mass = 176.5 kg
- Rover Weight on Mars = 656.7 N
- Average Weight per Wheel = 109.45 N
- Wheel Center Diameter = 0.262 m (with grouser bars)
- Wheel Outer Diameter = 0.232 m (with grouser bars)
- Wheel Width = 0.16 m

**Sojourner (Mars Pathfinder)**
- Mass = 10.5 kg
- Rover Weight on Mars = 39.07 N
- Average Weight per Wheel = 6.511 N
- Wheel Diameter = 0.137 m (with cleats)
- Wheel Width = 0.06 m

Isometric Views of Rover Wheel Envelopes to show relative sizes
defining Effective Ground Pressure
An engineering metric for rover comparisons and scaling

The Effective Ground Pressure, EGP, metric is defined as the average pressure under the average wheel. The average weight on a wheel is first found by dividing the total vehicle weight on a planetary body by the number of wheels. The EGP is found by dividing the average weight by the cross sectional area of the wheel's contact patch on the ground plane, after the wheel has sunk into a terrain so as to have a contact patch length of one wheel radius. In the case of non-cylindrical tires, the largest radius, usually at the mid-plane is used. When the wheel's periphery has cleats, lugs, or grouser bars; a determination is made as to the amount of their height added to the tire diameter, based on the projected area ratio of these tractive elements.
Cross-Sectional Area of each Wheel’s Contact Patch with the Ground Plane:
Determined via CAD Analysis

- **Mars Science Laboratory**: CS Area = 0.0901 m²
- **Mars Exploration Rover**: CS Area = 0.0173 m²
- **Mars Pathfinder**: CS Area = 0.00411 m²
Effective Ground Pressure Comparisons: Planetary Rovers on Mars

• Mars Pathfinder – *Sojourner*
  
  - EGP = Average Weight/CS Area = 6.511 N / 0.00411 m² = 1586 N/m²
  - = 1586 Pa (0.23 psi)

• Mars Exploration Rover – *Spirit and Opportunity*
  
  - EGP = Average Weight/CS Area = 109.45 N / 0.0173 m² = 6335 N/m²
  - = 6335 Pa (0.919 psi)

• Mars Science Laboratory - *Curiosity*
  
  - EGP = Average Weight/CS Area = 595.3 N / 0.0901 m² = 6609 N/m²
  - = 6609 Pa (0.959 psi)
Testing under mobility conditions was performed on a 5 meter square tilt-able platform called the Variable Terrain Tilt Platform (VTTP).

The slope of the VTTP could be set between 0 and 30 degrees.

The surface was initially bare, and later covered with dry and loose quartz sand.

Obstacles could also be attached to the platform.
DTM Rover driving cross-slope on the VTTP, at a 20 deg slope, and covered with 20 cm of dry, loose quartz sand
Mobility Dynamic Model
Original Contact Formulation

- Physical Idealizations in the **MSC.ADAMS** Rover Model
  - Rigid WEB with mass and inertia
  - Mass and stiffness based on FEM
  - Compliance in suspension, wheels, and torque tube
  - All struts and tubes modeled with Timoshenko beam forces
  - Differential relationship added algebraically
  - Empirical values for damping and friction
As a result of Spirit's mobility issues, a team led by the Project’s Deputy Principal Investigator, Prof. Ray Arvidson of Washington University in St. Louis, has begun employing Multi-Body Dynamic Simulations, utilizing the commercial software MSC.ADAMS, to analyze the wheel terrain interaction, or Terramechanics of Spirit in the hopes of freeing her.
View from the Front Hazard Avoidance Camera on Sol 1871. Note that Spirit has been driving in reverse, dragging its right-front wheel behind it. The right-front wheel has been un-drivable since ~ Sol 1000.

View from the Rear Hazard Avoidance Camera on Sol 1871. This image shows the reverse driving direction of Spirit with the right-rear wheel nearly fully embedded, and with the left-rear wheel buried up to the radius of the wheel.
Details of Spirit’s Embedding

Ground support software visualization of Spirit’s embedding

Rover color images, generated on the ground, from the Panoramic Cameras, showing the deployment of the robotic arm and the science instruments to the disturbed soft soils that having caused Spirit’s embedding.
MER SSTB (Surface System Test-Bed) Rover being driven into an embedding situation in a Simulant composed of Diatomaceous Earth and Fine Clay, to test extrication strategies for the Spirit rover
MSL Engineering Model being Tested on Dry, Loose Sand on a 20 Degree Slope