Some Thoughts on Simulations in Terramechanics

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Terramechanics

- **Terramechanics*, in a broad sense, is the study of the overall performance of terrestrial and extraterrestrial vehicles/machines in relation to its operating environment – the terrain.**

*** "xTerramechanics" is a branch of Terramechanics as applied to extraterrestrial missions.**

Terramechanics

- **The aim of Terramechanics is to provide guiding principles for the rational design, evaluation, selection and operation of terrestrial and extraterrestrial vehicles/machines.**
- **In the further development of this branch of applied mechanics and simulation models in Terramechanics, one should not lose sight of this fundamental objective.**

Simulation Models in Terramechanics

- **Simulations in general are intended to replicate the behavior of terrestrial or extraterrestrial vehicles/machines in the nature environment. This would provide a better understanding of the physical nature of the issues involved, leading to improvements in the design of future generations of vehicles /machines.**
- **The input terrain data to simulation models should be collected, wherever practicable, in its natural state under undisturbed conditions, to ensure that the predictions made by the models are relevant to the field conditions of interest.**

Simulation Models in Terramechanics

- **A well-developed simulation model would be useful in optimizing the design parameters of the type of vehicle/machine, for which the model is intended.**
- **It may or may not lead to the creation of radically new (or revolutionary) design concepts for terrestrial or extraterrestrial vehicles/machines, however comprehensive or detailed the simulation model is.**

Simulation Models in Terramechanics

- **Simulation models have to be developed and implemented in such a manner that will be conducive to practical solutions and will appeal to engineering practitioners.**
- **The success of any simulation model in Terramechanics is judged by its impact on the design (or operation) of terrestrial or extraterrestrial vehicles/machines with enhanced performance.**

Applications of Simulation Model *NWVPM* to Evaluating Rover Wheel Mobility

Computer-Aided Method *NWVPM*

- **It was originally developed for evaluating the effects of design on the steady-state performance of terrestrial wheeled vehicles.**
- **Recent studies have shown that it can be extended to the evaluation of the mobility and design of extraterrestrial rover wheels.**

***NWVPM* is based on the analysis of and experimental data on the normal and shear stress distributions on the wheel-terrain interface.**

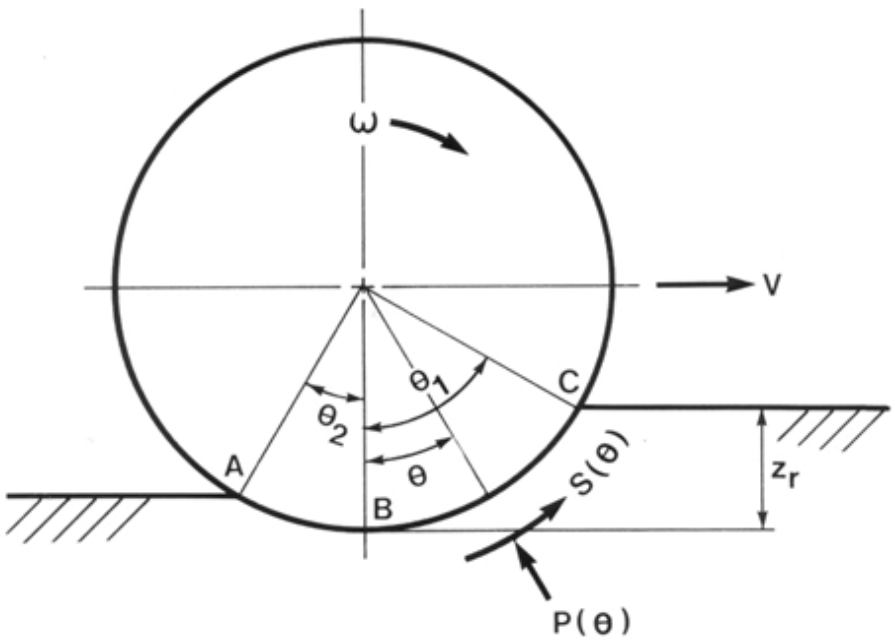
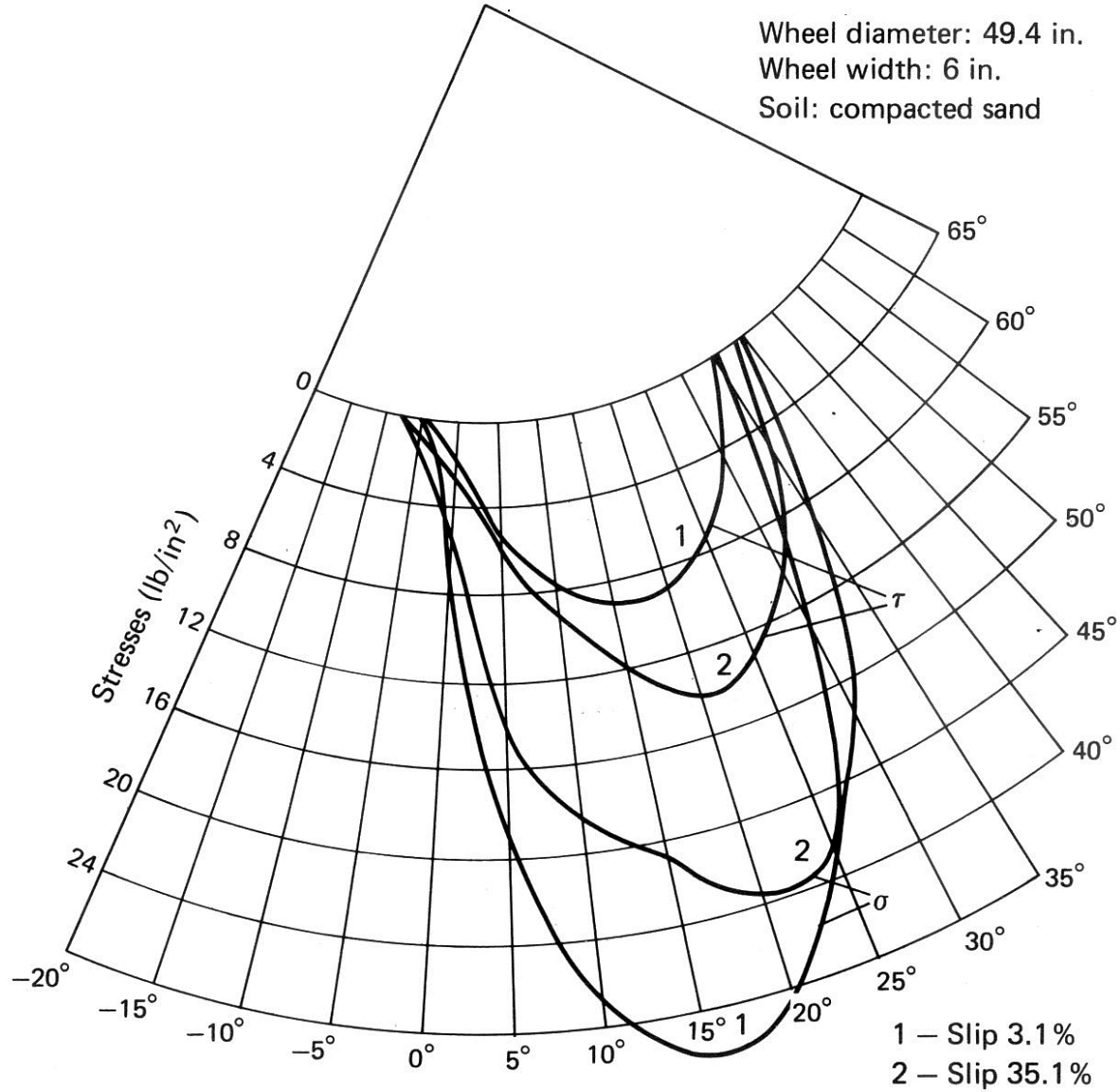


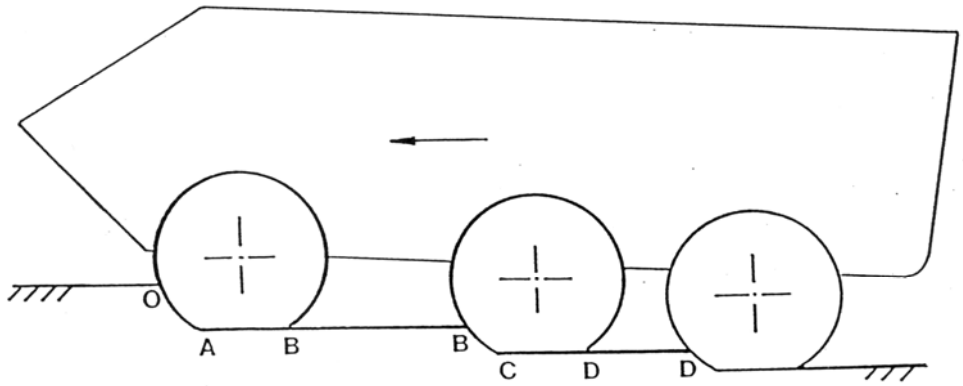
Fig. 9.1. The improved model for tire-terrain interaction for a tire in the rigid operating mode.

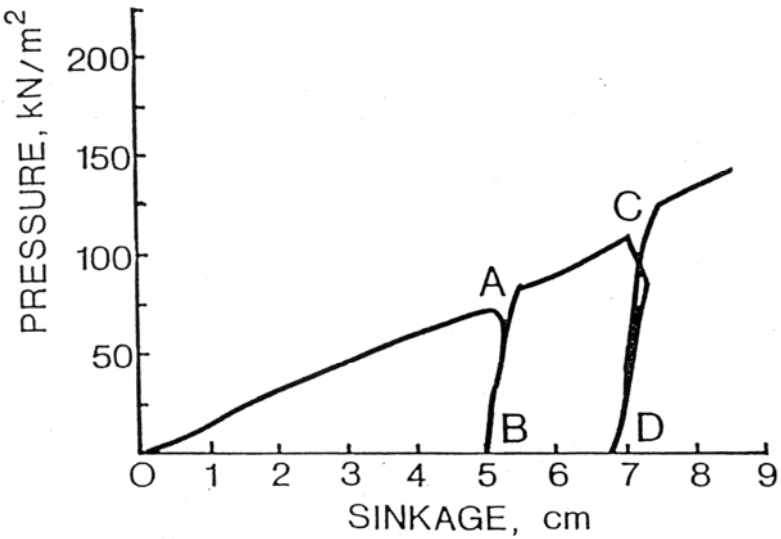


Measured normal and shear stress distributions on the rim of a rigid wheel on compacted sand. (Onafeko & Reece, *Journal of Terramechanics,* Vol. 4(1), 1967.)

NWVPM

- **Major vehicle design features considered:**
  - **Vehicle weight and axle load distribution**
  - **Axle suspension stiffness**
  - **Type of the axle (driven or non-driven)**
  - **Tread of the axle (distance between the centers of left- and right-hand side wheels)**
  - **Wheel loads, dimensions and other parameters**
  - **“Multi-pass” effects of wheels in a multi-axle vehicle**
  - **Inter-axle load transfer**



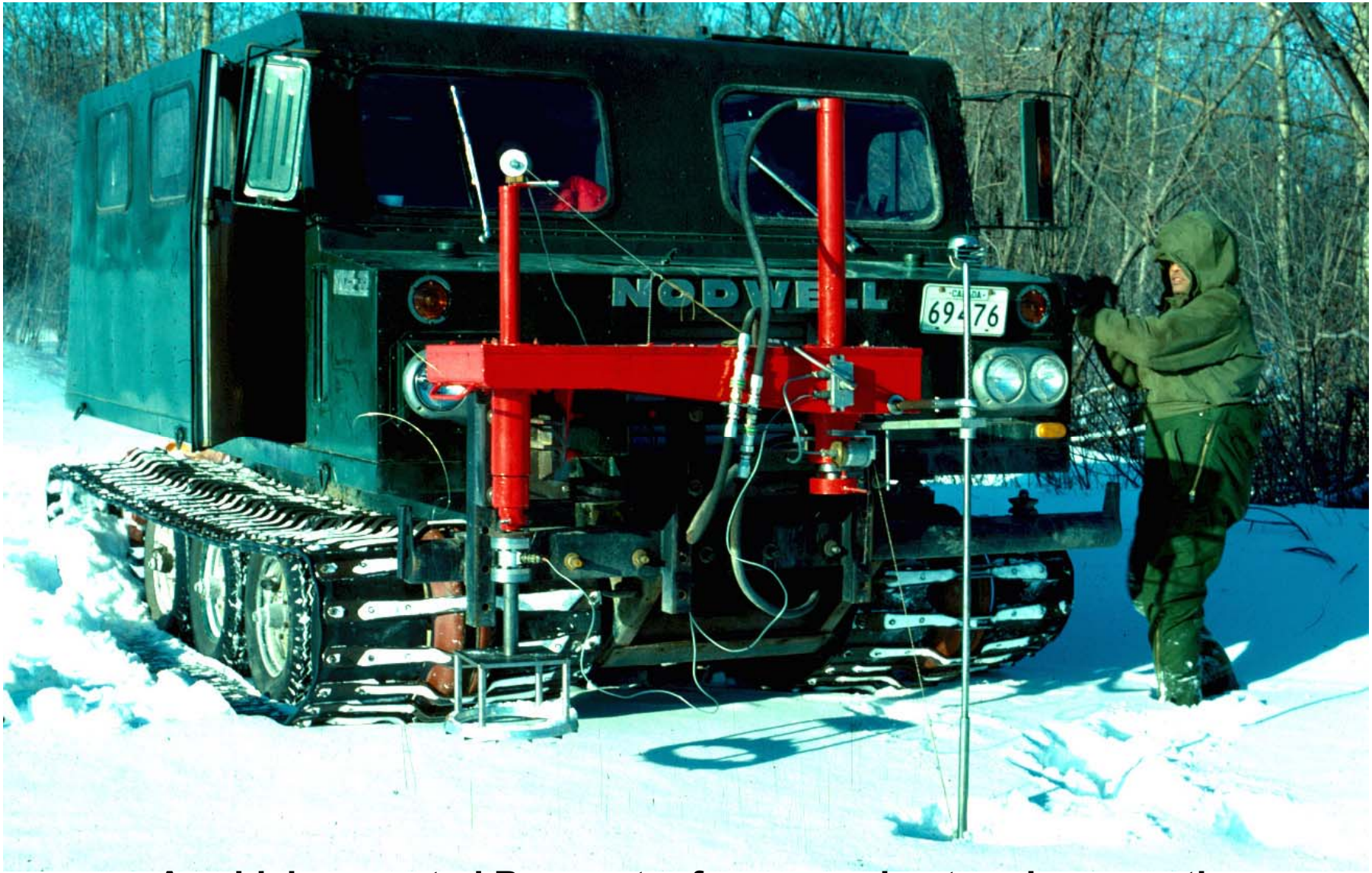


Response of a mineral soil to repetitive loading.

Multi-pass effects (Wong, et al., 1984)

NWVPM

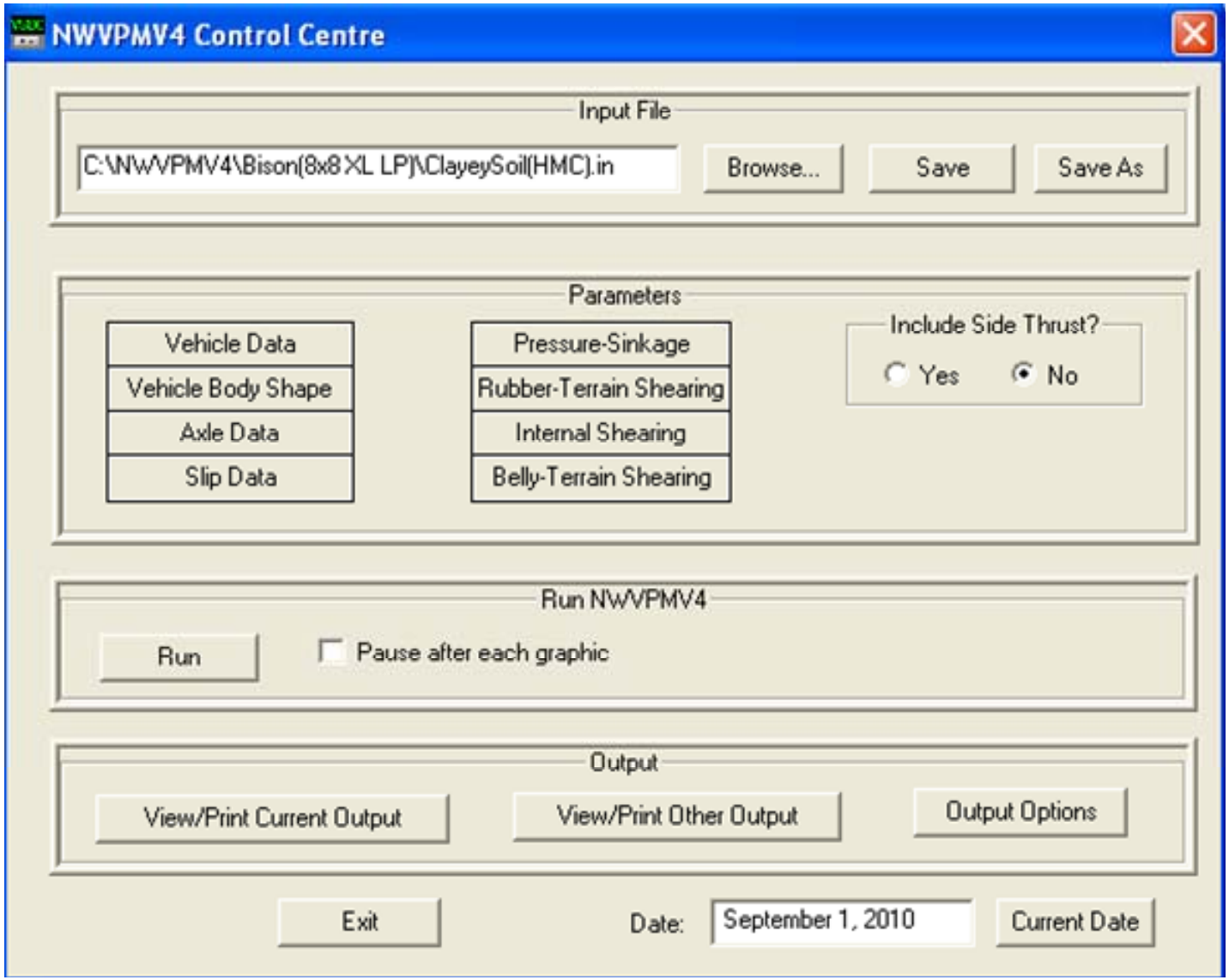
- **Terrain parameters input to *NWVPM* are obtained using the Bevameter.**
- **They include parameters for characterizing the pressure-sinkage relation, shear strength, and response to repetitive normal and shear loading of the terrain.**
- **Terrain data are processed on-board of a mobile platform using a special software.**
- **Together with a reduced-order simulation model (such as *NWVPM*), it is feasible to predict, close to real-time, rover mobility during driving operations on-board of a rover.**



A vehicle-mounted Bevameter for measuring terrain properties.

A computerized data processing system for a vehicle-mounted Bevameter.

Dr. Bekker examining the computerized data processing system for a vehicle-mounted Bevameter.



Control centre for operating *NWVPM* as displayed on the computer monitor.

NWVPM

- **Capabilities**
  - **Prediction of the tractive performance of wheeled vehicles/rovers, including sinkage, motion resistance, thrust, drawbar pull, tractive efficiency, etc. as functions of wheel slip.**
  - **Selection of a suitable wheeled vehicle/rover configuration and/or its wheels in a given operating environment.**

Applications of *NWVPM* to Evaluating Lunar Rover Wheel Mobility

- In collaboration with NASA Glenn Research Center (GRC), the potential application of *NWVPM* to the evaluation of the mobility of extraterrestrial rovers/rover wheels was evaluated.

- The correlation between the performances of wheel candidates for the Lunar Roving Vehicle predicted by *NWVPM* and test data obtained by U.S. Army Waterways Experiment Station was examined. The details are published in a paper in the *Journal of Automobile Engineering,* Proceedings of the Institution of Mechanical Engineers, Part D, Vol. 222 (D11), 2008.

Journal of Automobile Engineering
Proceedings of the Institution of Mechanical Engineers, Part D
Vol. 222, No. D11, November 2008, pp. 1939 -1954.

Study of the correlation between the performances of lunar vehicle wheels predicted by the Nepean wheeled vehicle performance model and test data

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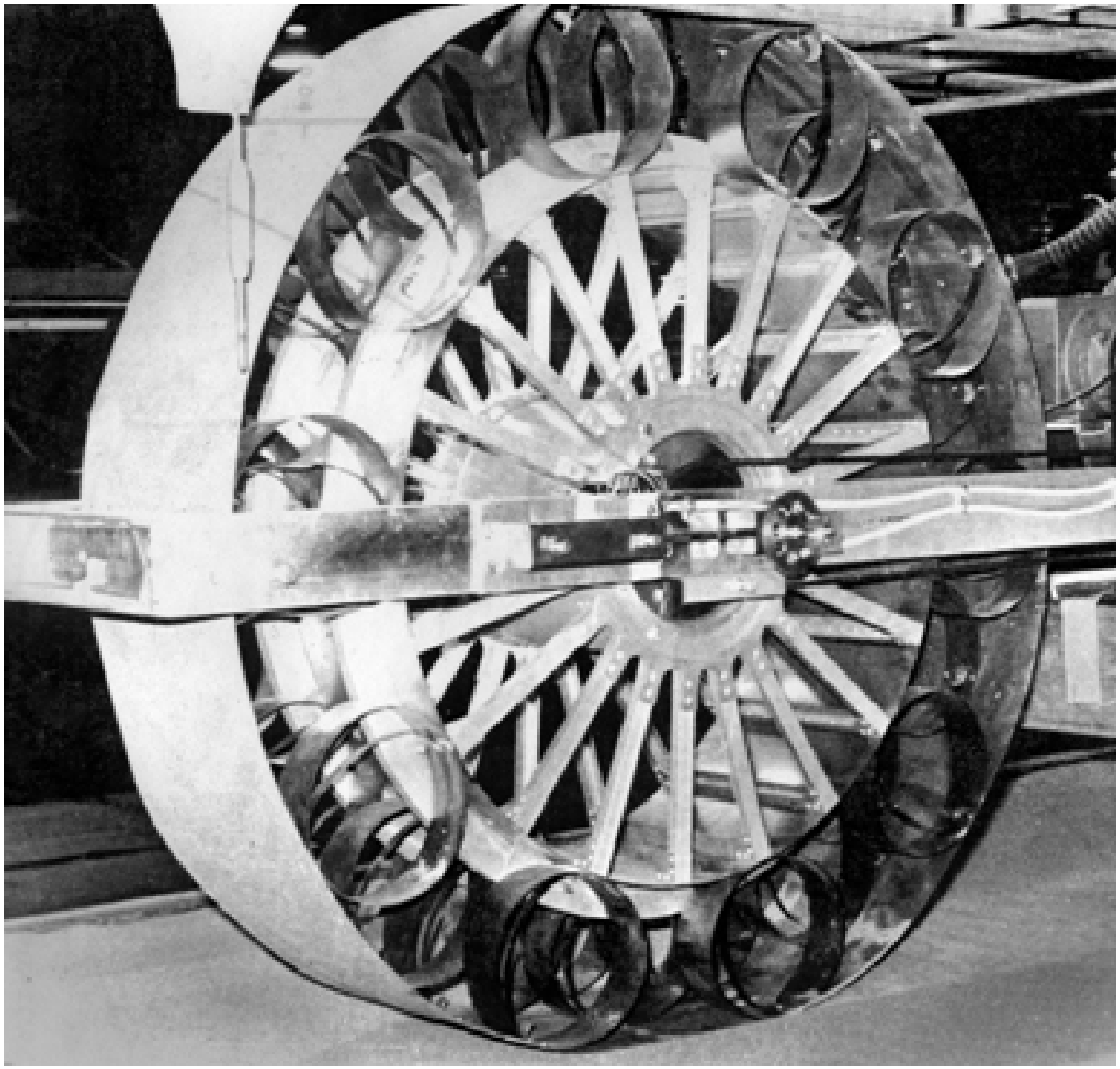
- Wire-mesh wheels for the Lunar Roving Vehicle for NASA's Apollo missions, developed by the Boeing-General Motors team, are woven with steel wire and girded with titanium chevrons. They look like skeletons of pneumatic tires that support earthbound vehicles.
- Weighing only 12 lbs, they are compatible with the vacuum and temperature extremes on the Lunar surface. (*Source:* NASA)

Comparison of the predicted drawbar pull to normal load ratio at 20% slip (P_{20} / W) by *NWVPM* with the measured for the Boeing-GM IV and VI wheels on dry sand S1 (*Wong and Asnani, 2008*)

Wheel type	Normal load (N)	Contact (Ground) pressure (kPa)	Measured* P_{20} / W (%)	Predicted** P_{20} / W (%)	Predicted / Measured (%)
Boeing -GM IV	311	13.31	28	29.8	106.4
Boeing -GM VI	311	4.04	38.4	41.5†	108.1
Boeing -GM VI	311	4.42	38.4	40.9†	106.5

*** *Source:* WES Technical Report M-70-2, by Freitag, Green, and Melzer, 1970.**
**** Based on average Bekker soil values and estimated *K* = 0.5 cm.**
†Taking into account the estimated coefficient of motion resistance due to wheel flexing of 4.3%.



Hoop-spring wheel developed by Bendix for the Lunar Roving Vehicle.
(*Source:* NASA)

Comparison of the predicted drawbar pull to normal load ratio at 20% slip (P_{20} / W) by *NWVPM* with the measured for the Bendix lunar wheel on dry sand S_1 (*Wong* and *Asnani*, 2008)

Normal Load, N	Contact (Ground) Pressure, kPa	Measured* P_{20} / W, %	Predicted** P_{20} / W, %	Predicted / Measured, %
67	2.76	42.4	37.2	87.7
133	2.58	45.8	45.2	98.7
311	3.93	46.3	47.3	102.2

* *Source:* WES Technical Report M-70-2, by Freitag, Green, and Melzer, 1970.
** Based on average Bekker soil values and estimated *K* = 0.5 cm.

Applications of *NWVPM* to Evaluating the Mobility of Extraterrestrial Rovers

- Results of the study show that there is a reasonably close agreement between the predictions by *NWVPM* and test data.
- This indicates that *NWVPM* can be used as an engineering tool for evaluating or comparing the mobility of extraterrestrial rover wheels.
- The Surface Mobility Technology Team of NASA GRC has used *NWVPM* in the evaluation of extraterrestrial rovers and rover wheels for future missions.

Prediction of Rover Performance on Extraterrestrial Bodies Based on Test Data Obtained on Earth

- **Test data obtained on earth, with loads applied to the wheels corresponding to those on extraterrestrial bodies, while soil simulants are subject to earth gravity, are not necessarily representative of the performance of the wheels on extraterrestrial bodies (such as, wheel sinkage and motion resistance).**
- **The development of an appropriate methodology for predicting the performance of rovers on extraterrestrial bodies based on test data obtained on earth is needed.**

A method for predicting the effects of gravity on rover wheel performance on extraterrestrial bodies, based on test results obtained on earth, is being developed. Results obtained so far indicate that the correlations between the predictions obtained using the method and available experimental data are reasonably close. Details of the method and its experimental substantiation will be published in the not too distant future.

Challenges and Opportunities

- **In parallel with formulating new models for simulating terrain behavior, the procedures/techniques for acquiring the required input terrain parameters to the models should be developed. Otherwise the potential of their predictive capability could not be realized.**

Challenges and Opportunities

- **To be useful for guiding the development of future generations of vehicles/ machines, in formulating new simulation models for vehicle/machine-terrain interaction, the design features of the vehicles/machines should be fully taken into consideration.**
- **This is because the design features of the vehicle/machine have a significant impact on its interaction with the terrain.**

Challenges and Opportunities

In view of the complexity in modeling vehicle/machine-terrain interaction and the variability of terrain conditions in the field, it is suggested that for the foreseeable future, the role of a simulation model is to provide *a practical and reliable platform for evaluating the design or performance of vehicles/machines on a relative basis*.

The End