Third Edition

TERRAMECHANICS AND OFF-ROAD VEHICLE ENGINEERING

TERRAIN BEHAVIOUR AND OFF-ROAD MOBILITY

J. Y. WONG

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Terrain Behaviour and Off-Road Mobility

Third Edition

J.Y. Wong
Professor Emeritus
Department of Mechanical and Aerospace Engineering
Carleton University, Ottawa
Ontario, Canada

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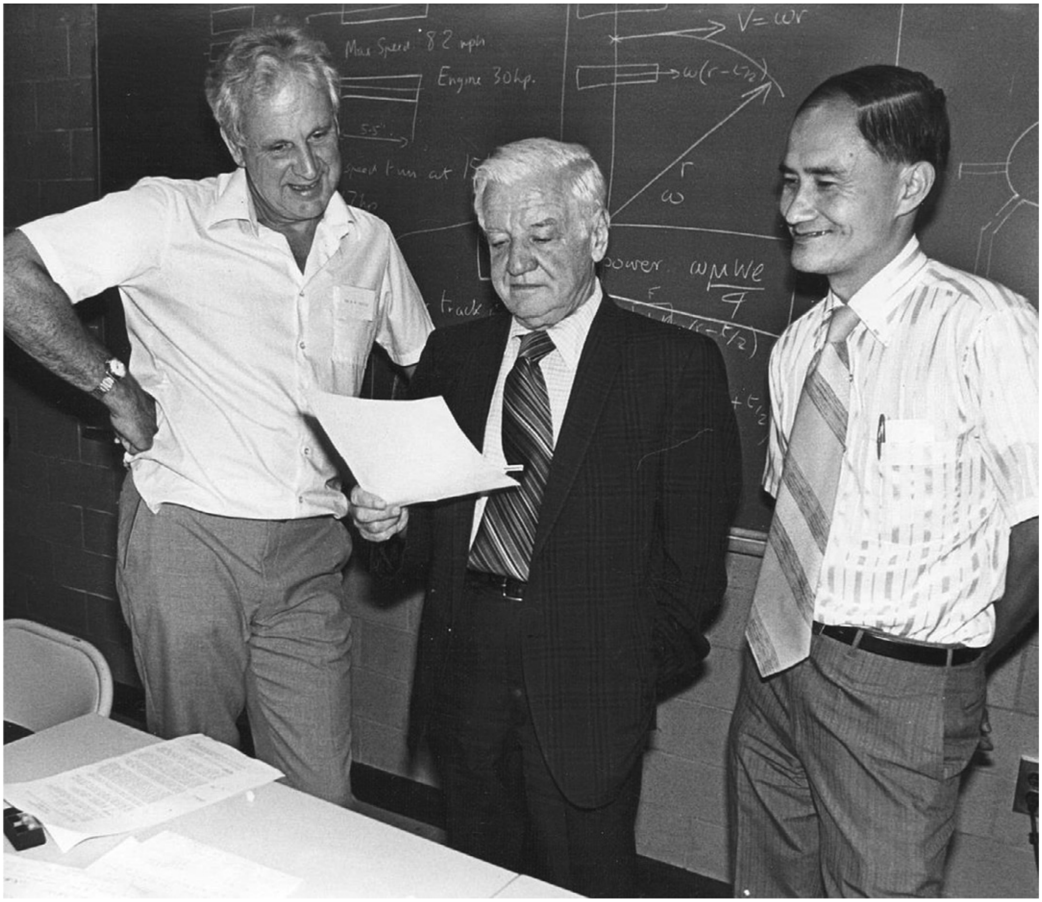
To the Pioneers of Terramechanics

Dr. Mieczyslaw Gregory Bekker, *1905–1989*

who coined the term 'terramechanics' in 1960 and laid the foundation for this discipline.

Dr. Alan Richard Reece, *1927–2012*

who was the first President, International Society for Terrain-Vehicle Systems and founding Editor, Journal of Terramechanics.



Dr. Bekker (centre), Dr. Reece (left), and the Author (right) at the professional development program '*Terrain-Vehicle Systems Analysis*', Carleton University, Ottawa, Canada, 1978.

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Author Biography

Dr. Jo Yung Wong is Professor Emeritus, Department of Mechanical and Aerospace Engineering, Carleton University, Ottawa, Canada. He received his B.Eng. from Tsinghua University, China, and Ph.D. and D.Sc. from the University of Newcastle upon Tyne, England.

He has been engaged in research and development of ground vehicle technology for decades. Many of his research findings have found applications in industry. In recognition of his outstanding contributions to the field, Dr. Wong has been presented with many awards by learned societies, including the *George Stephenson Prize, Starley Premium Award* (twice), and *Engineering Applied to Agriculture Award* of the Institution of Mechanical Engineers, United Kingdom, and the *William F. Milliken Award* of the American Society of Mechanical Engineers.

Dr. Wong has published extensively with many research publications. In addition to this book, he is the author of another book, *Theory of Ground Vehicles*, currently in its fifth edition, published by John Wiley, New Jersey, United States. The translations of its earlier editions into Russian and Chinese languages were published in Moscow and Beijing, respectively. These two books have been widely adopted as text or reference for courses in vehicle engineering or related fields at many universities and used by professionals in industry and research institutions around the world.

He is currently on the advisory/editorial boards of a number of international vehicle engineering journals, including the *Journal of Terramechanics, Vehicle System Dynamics, International Journal of Heavy Vehicle Systems*, and *International Journal of Vehicle Performance*. He has also served on the editorial board of the *Journal of Automobile Engineering*, Part D of the Proceedings of the Institution of Mechanical Engineers, United Kingdom.

Dr. Wong is Fellow of the American Society of Mechanical Engineers, Institution of Mechanical Engineers, Canadian Society for Mechanical Engineering, and International Society for Terrain-Vehicle Systems. He is a former President of the International Society for Terrain-Vehicle Systems.

He has been a consultant to major vehicle manufacturers and governmental agencies of many countries. He has been invited to present professional development programs and seminars on ground vehicle technology in North America, Europe, and Asia. At the invitations of the Glenn Research Center of the U.S. National Aeronautics and Space Administration (NASA), European Space Research and Technology Centre of the European Space Agency (ESA), and Canadian Space Agency (CSA), he presented special professional development programs on *Applications of Terramechanics to Evaluating Extraterrestrial Rover Mobility*.

Preface to the Third Edition

To expedite new product developments in the off-road vehicle industry, or to improve the capability of making more reliable mobility predictions and assessments in operational planning and field deployment in the off-road vehicle user communities, including both civilian and defence sectors, there is a continual need for the development of improved off-road mobility simulation models. For example, in the defence sector, the empirically based NATO Reference Mobility Model (NRMM), originally released in 1979, is to be superseded by the physics-based Next-Generation NATO Reference Mobility Model (NG-NRMM). The guidance for standards applicable to the development of NG-NRMM is stipulated in the NATO Standard AMSP-06 promulgated in July 2021.

Measurement and characterization of terrain engineering properties is one of the important issues for the development of improved simulation models for vehicle mobility. Among the various parameters currently in use for characterizing terrain behaviour pertinent to vehicle mobility, the Bekker-Wong terrain parameters measured by the bevameter have gained wide acceptance and have been included in the 2020 International Society for Terrain-Vehicle Systems Standards.

With the interest in the exploration of extraterrestrial surfaces, such as that on the Moon, Mars, and beyond, shown by an increasing number of nations, terramechanics principles have been applied to guiding the development of extraterrestrial rovers and to evaluating their mobility.

In this third edition, the topics noted above have been included and discussions of some other topics in the previous editions have been expanded. In the presentation, emphasis continues to be placed on elucidating the physical nature and mechanics of vehicle-terrain interactions as in previous editions.

The number of chapters in this edition has been expanded to 13 from 12 in the previous edition. Chapter 1 outlines the role of terramechanics in guiding the development and evaluation of off-road vehicles from the mobility perspective. Chapter 2 highlights various models for terrain behaviour, ranging from those based on the theory of elasticity to the theory of plastic equilibrium. Discussions of the applications of the finite element method (FEM) and discrete element method (DEM) to modelling terrain behaviour are expanded. Prospects for further development of the DEM for applications to terramechanics are highlighted. Chapter 3 reviews the instrumentation and techniques currently in use for measuring terrain engineering properties in the field. Chapter 4 presents the Bekker-Wong terrain parameters for characterizing load bearing and internal shearing behaviour of terrain, terrain response to repetitive normal and shear loadings, rubber-terrain shearing (for evaluating the performance of rubber tyres, rubber tracks, or metal tracks with rubber pads), as well as vehicle belly material-terrain shearing (for studying vehicle belly-terrain interaction when the sinkage of vehicle running gear is greater than vehicle ground clearance). Chapter 5 outlines the basic factors affecting vehicle mobility and metrics for evaluating vehicle cross-country performance. Chapter 6 presents various approaches to evaluating off-road mobility ranging from empirically based methods to the physics-based Next-Generation NATO Reference Mobility Model. Chapter 7 presents the physics-based model NTVPM (Nepean Tracked Vehicle Performance Model) for predicting the cross-country performance of vehicles with flexible tracks and its experimental substantiation. Chapter 8 highlights the applications of NTVPM to evaluating the effects of design features on performance of vehicles with flexible tracks, as well as examples of its application to guiding the development of new products in industry. Chapter 9 outlines a physics-based model RTVPM (Rigid-Link Tracked Vehicle Performance Model) for evaluating the cross-country performance of vehicles with long-pitch link tracks, such as agricultural and industrial tracked vehicles, and its experimental substantiation. Chapter 10 highlights various methods ranging from empirical to analytical for evaluating wheel (tyre) performance on deformable terrain, while Chapter 11 presents the physics-based simulation model NWVPM (Nepean Wheeled Vehicle Performance Model) for evaluating wheeled vehicle performance and its experimental substantiation and applications. Chapter 12 examines the issues of wheels vs. tracks from a mobility perspective and physics-based mobility metrics for evaluating off-road vehicle cross-country performance. Chapter 13 explores the applications of terramechanics to evaluating extraterrestrial rover mobility. It outlines a method for predicting rover mobility on extraterrestrial surfaces based on test results obtained on the Earth's surface. It also highlights the basic features of the simulator Artemis for rover traverses on extraterrestrial surfaces.

This book is intended to serve as text or reference for courses in off-road vehicle engineering at universities and colleges, as well as technical reference for engineers and researchers in the off-road vehicle industry.

The technical assistance provided by Jon Preston-Thomas and Wei Huang in the preparation of the manuscript for this edition is much appreciated.

This edition is dedicated to the pioneers of terramechanics—Dr. M.G. Bekker and Dr. A.R. Reece.

Dr. Bekker coined the term "terramechanics", which appeared in the subtitle of his book *Off-The-Road Locomotion – Research and Development in Terramechanics*, published by the University of Michigan Press, 1960. Together with his other two books, *Theory of Land Locomotion* and *Introduction to Terrain-Vehicle Systems*, published by the University of Michigan Press in 1956 and 1969, respectively, his works laid the foundation of this discipline. He made outstanding contributions to the research and development of the mobility system of the crewed Lunar Roving Vehicle (LRV) for NASA's Apollo missions 15, 16, and 17 in the early 1970s. The LRV was successfully operated by astronauts in the exploration of the lunar surface. I had the good fortune to work with Dr. Bekker on a research program sponsored by the National Research Council Canada in the early 1980s and on jointly presenting a series of professional development programs on *'Terrain-Vehicle Systems Analysis'* at Carleton University, Ottawa, Canada, in 1976, 1977, 1978 (with Dr. A.R. Reece as a special lecturer), 1980 (with J.R. Radforth as a special lecturer), and 1985. A similar program was also jointly presented in Sweden at the invitation of the Swedish Society for Collaboration of Terrain-Vehicle Research (SFM) in 1978.

Dr. Reece was the first President, International Society for Terrain-Vehicle Systems, and founding Editor, *Journal of Terramechanics*. He was my graduate study advisor at the University of Newcastle upon Tyne, England. He later founded Soil Machine Dynamics Ltd. (SMD), which developed and manufactured special machinery for burying oil and gas pipelines and telecommunication cables in the seabed. For its highly innovative products, SMD was presented with the British Royal Academy of Engineering MacRobert Award and the Queen's Awards for Innovation and for Enterprise (International Trade).

Jo Yung Wong
Toronto, Canada

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Preface to the Second Edition

Since the publication of the first edition of this book in 1989, notable progress has been made in terramechanics, which is the study of the dynamics of an off-road vehicle in relation to its environment—the terrain. Understanding of the mechanics of vehicle–terrain interaction has been improved. New techniques have been introduced into the modelling of terrain behaviour. A series of computer-aided methods for performance and design evaluation of off-road vehicles from the traction perspective, incorporating recent advancements in terramechanics, have been further developed. These methods have been gaining acceptance in industry in the development of new products. Continual interest in improving vehicle mobility over a wider range of environments and renewed enthusiasm for the exploration of the Moon, Mars, and beyond shown by an increasing number of nations have given new impetus to the further development of terramechanics. To reflect these and other advancements in the field and to serve the changing needs of the professional and higher educational communities, time is ripe for this second edition.

While new topics are introduced and data are updated in this edition, the objective and format remain similar to those of the previous edition. The fundamentals of terramechanics underlying the rational development and design of off-road vehicles are emphasized. As the performance of off-road vehicles over unprepared terrain constitutes a basic issue in vehicle mobility, this book focuses on the study of vehicle–terrain interaction from the traction perspective.

To better serve the higher educational community in the fields of automotive engineering, off-road vehicle engineering, and agricultural and biological engineering, examples of the applications of the principles of terramechanics to solving engineering problems are given. Practical problems that may be assigned to senior undergraduate or postgraduate students as part of their study programme are also included in this new edition.

The number of chapters has been expanded to 12 in this edition from eight in the previous edition. Chapter 1 provides an introduction to the subject of terramechanics, outlines its roles, and presents outstanding examples of its practical applications. A brief review of the modelling of terrain behaviour is presented in Chapter 2. The fundamentals of the theories of elasticity, plastic equilibrium, and critical state soil mechanics, as applied to the study of vehicle–terrain interaction, are outlined. The applications of the finite element method (FEM) and the discrete (distinct) element method (DEM) to the modelling of terrain are reviewed. While these theories or modelling techniques provide a foundation for an understanding of some aspects of the physical nature of vehicle–terrain interaction, there are limitations to their applications in practice, particularly in modelling behaviour of natural terrain. Chapter 3 describes the techniques and instrumentation currently used for measuring terrain behaviour in the field. The responses of various types of natural terrain to normal and repetitive loading observed in the field are discussed in Chapter 4. This provides the terrain information needed for predicting the sinkage of the vehicle running gear and the normal pressure distribution on the vehicle–terrain interface. Chapter 5 describes the shear strengths of various types of natural terrain measured in the field and their characterization. This provides the required terrain information for predicting the tractive capability of off-road vehicles in the field. Criteria commonly used for evaluating the performance of various types of off-road vehicle are reviewed in Chapter 6. Empirical and semi-empirical methods for predicting tracked vehicle performance are discussed in Chapter 7. Chapter 8 outlines the analytical basis for the computer-aided method NTVPM (Nepean Tracked Vehicle Performance Model) for performance and design evaluation of vehicles with flexible tracks, such as military and cross-country transport vehicles. The experimental validation of NTVPM is also described. Applications of NTVPM to parametric analyses of vehicle designs are discussed in Chapter 9. Examples of its applications to the development of new products in off-road vehicle industry are presented. Chapter 10 outlines the analytical basis for the computer-aided method RTVPM (Rigid-Link Tracked Vehicle Performance Model) for performance and design evaluation of vehicles with long-pitch link tracks, such as industrial and agricultural tractors. The experimental validation of RTVPM and its applications to parametric analyses are presented. Chapter 11 presents empirical and semi-empirical methods for predicting wheel and wheeled vehicle performance. The analytical basis for the computer-aided method NWVPM (Nepean Wheeled Vehicle Performance Model) for predicting the performances of wheels and wheeled vehicles is outlined in Chapter 12. As an example, the application of NWVPM to the evaluation of the performance of lunar vehicle wheels is presented.

Some of the material included in this new edition has been presented at professional development programmes and seminars in many countries. These included staff training programmes on the applications of terramechanics to the evaluation of planetary rover mobility, presented at the European Space Research and Technology Centre (ESTEC) of the European Space Agency (ESA) and at the Glenn Research Center, National Aeronautics and Space Administration (NASA), U.S.

This new edition includes some of the results of recent research on off-road vehicle mobility carried out by the author together with his associates at Carleton University and at Vehicle Systems Development Corporation (VSDC), Ottawa, Canada. The author wishes to express his appreciation to his former research staff, postdoctoral fellows, and graduate students at Carleton, and to his associates at VSDC for their contributions, particularly Jon Preston-Thomas, the late Michael Garber, Yuli Gao, Mike Galway, and Wei Huang. Appreciation is due also to many organizations, in private and public sectors, for their generous support for our research over the years.

Jo Yung Wong
Ottawa, Canada

Preface to the First Edition

In the past few decades, the continual demand for greater mobility over a wider range of terrains and in all seasons by agricultural, construction, and cross-country transport industries and the military has stimulated a great deal of interest in the study of vehicle mobility over unprepared terrain. A large volume of research papers on this subject has been published in journals and conference proceedings of learned societies. A variety of methods for predicting and evaluating off-road vehicle performance, ranging from entirely empirical to highly theoretical, has been proposed or developed. However, methods that will enable the design engineer or the procurement manager to conduct a comprehensive yet realistic evaluation of competing vehicle designs appear to be lacking. This prompted the author of this book to embark, more than a decade ago, on a series of research programmes aimed at filling this gap. The objective is to establish mathematical models for vehicle–terrain systems that will enable the engineering practitioner to evaluate, on a rational basis, a wide range of options and to select an appropriate vehicle configuration for a given mission and environment. To be useful to the design engineer or the procurement manager, the models should take into account all major vehicle design and operational parameters as well as pertinent terrain characteristics.

After more than a decade of intense effort, a series of computer-aided methods (computer simulation models) for predicting and evaluating the performance of tracked and wheeled vehicles, which meet the basic objective outlined before, have emerged. These methods have since been used to assist off-road vehicle manufacturers in developing new products and governmental agencies in evaluating vehicle candidates with most encouraging results. The encouragement that these developments have effected has convinced the author to put these pages together, with the hope that this book may enhance the interest of professionals engaged in the field of off-road vehicle mobility.

This book summarizes some of the research and development work on the computer-aided methods for evaluating off-road vehicle performance carried out by the author and his associates at the Transport Technology Research Laboratory, Carleton University, and Vehicle Systems Development Corporation, Ottawa, Canada. Chapter 1 provides an introduction to the subject of terramechanics and outlines its roles and basic issues. Chapter 2 describes the techniques and instrumentation for measuring terrain behaviour. An understanding of the mechanical properties of the terrain is of importance in the prediction and evaluation of off-road vehicle performance, as the behaviour of the terrain quite often imposes severe limitations to vehicle mobility. Chapter 3 describes the responses of various types of natural terrain to normal and repetitive loading. This provides information for predicting the sinkage of the vehicle running gear and the normal pressure distribution on the vehicle–terrain interface. Chapter 4 describes the shear strength of various types of natural terrain. This provides information for predicting the tractive capability of off-road vehicles. Chapter 5 reviews some of the methods previously developed for predicting the performance of tracked vehicles. Chapter 6 outlines the analytical framework for the development of computer-aided methods for evaluating tracked vehicle performance, while Chapter 7 illustrates some of the applications of the computer-aided methods to the parametric analysis of tracked vehicle design and performance. Chapter 8 reviews some of the methods previously developed for predicting the performance of tyres, while Chapter 9 outlines the recently developed computer-aided methods for evaluating the performance of tyres and wheeled vehicles and illustrates their applications.

Some of the material included in this book has been presented at seminars and professional development programmes in Canada, China, Italy, Germany, Singapore, Spain, Sweden, the United Kingdom, and the United States. Some of these seminars were jointly offered with the late Dr. M.G. Bekker during the period from 1976 to 1985.

The computer-aided methods presented in this book represent recent advances in the methodology for predicting and evaluating off-road vehicle performance. This does not mean, however, that further development of the methods described is not required. If and when better mathematical models for vehicle–terrain interaction and characterizing terrain behaviour are available, they could readily be fitted into the framework presented here to make an even more comprehensive and precise picture.

Many organizations have supported the research upon which this book is based. In particular, the author wishes to record the support provided by the Canadian Department of National Defence, National Research Council of Canada, Natural Sciences and Engineering Research Council of Canada, and Vehicle Systems Development Corporation. In writing this book, the author has drawn much on the experience acquired from working with many industrial and research organizations, including Hagglunds Vehicle AB of Sweden, U.S. Naval Civil Engineering Laboratory, Institute for Earthmoving Machinery and Off-Road Vehicles (CEMOTER) of the Italian National Research Council, and Vehicle Mobility Section, Defence Research Establishment, Suffield, and other branches of the Canadian Department of National Defence. This acknowledgement does not imply, however, that the views expressed in this book necessarily represent those of these organizations.

The author acknowledges with gratitude the inspiration derived from collaboration and discussions with many colleagues in industry, research organizations, and universities. He is indebted to Dr. A.R. Reece, formerly with the University of Newcastle upon Tyne and now Managing Director, Soil Machine Dynamics Ltd, England, and the late Dr. M.G. Bekker for their valued encouragement and stimulation. The author also wishes to express his appreciation to the staff members and graduate students at the Transport Technology Research Laboratory, Carleton University, and to his associates at Vehicle Systems Development Corporation for their contributions to the research work presented in this book. He is especially indebted to Mr. J. Preston-Thomas of Vehicle Systems Development Corporation for his contributions to the development of the computer-aided methods for evaluating off-road vehicle performance and for reviewing the manuscript.

Jo Yung Wong
Ottawa, Canada

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Conversion Factors

Quantity	U.S. customary unit	SI equivalent
Acceleration	ft/s^2	0.3048 m/s^2
Area	ft^2	0.0929 m^2
	in^2	645.2 mm^2
Energy	ft·lb	1.356 J
Force	lb	4.448 N
Length	ft	0.3048 m
	in	25.4 mm
	mile	1.609 km
Mass	slug	14.59 kg
	ton	907.2 kg
Moment of a force	lb·ft	1.356 N·m
Power	hp	745.7 W
Pressure or stress	lb/ft^2	47.88 Pa (N/m^2)
	lb/in^2 (psi)	6.895 kPa (kN/m^2)
Speed	ft/s	0.3048 m/s
	mph	1.609 km/h
Volume	ft^3	0.02832 m^3
	in^3	16.39 cm^3
	gal (liquids)	3.785 L

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Abbreviations and Acronyms

ANSI	American National Standards Institute
ARTEMIS	Adams-based Rover Terramechanics and Mobility Interaction Simulator
ASABE	American Society of Agricultural and Biological Engineers
ASAE	American Society of Agricultural Engineers (name changed to ASABE in 2005)
ASTM	American Society for Testing and Materials
CI	cone index
DEM	discrete (distinct) element method
FEM	finite element method
ISTVS	International Society for Terrain-Vehicle Systems
MMP	mean maximum pressure
NASA	U.S. National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NG-NRMM	Next-Generation NATO Reference Mobility Model
NRMM	NATO Reference Mobility Model
NTVPM	Nepean Tracked Vehicle Performance Model
NWVPM	Nepean Wheeled Vehicle Performance Model
RCI	rating cone index
RTVPM	Rigid-Link Tracked Vehicle Performance Model
SAE	Society of Automotive Engineers International
USCS	Unified Soil Classification System
VCI	vehicle cone index
WES	U.S. Army Corps of Engineers Waterways Experiment Station

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