Man has a long history of involvement in off-road locomotion, perhaps since the invention of the wheel about 3500 BC. Powered off-road vehicles have come into wide use in many parts of the world in agriculture, construction, cross-country transportation and military operations since the turn of last century. In spite of rapid progress in technology, the development of cross-country vehicles has, for a long period of time, been guided by empiricism and the ‘cut and try’ methodology. Systematic studies of the principles underlying the rational development of off-road vehicles did not receive significant attention until the middle of the 20th century. The publication of Dr M.G. Bekker’s classic treatises, Theory of Land Locomotion in 1956 and Off-the-Road Locomotion and Introduction to Terrain–Vehicle Systems in the 1960s, stimulated a great deal of interest in the systematic development of the principles of land locomotion mechanics (Bekker, 1956, 1960, 1969). His pioneering work and unique contributions laid the foundation for a distinct branch of applied mechanics, which has now become known as ‘Terramechanics’.

In a broad sense, terramechanics is the study of the overall performance of a machine in relation to its operating environment – the terrain. It has two main branches: terrain–vehicle mechanics and terrain–implement mechanics. Terrain–vehicle mechanics is concerned with the tractive performance of a vehicle over unprepared terrain, ride quality over unprepared surfaces, handling, obstacle negotiation, water-crossing and other related topics. Terrain–implement mechanics, on the other hand, deals with the performance of terrain-working machinery, such as soil cultivating and earthmoving equipment.

The aim of terramechanics is to provide guiding principles for the rational development, design, and evaluation of off-road vehicles and terrain-working machinery. In recent years, the growing concern over energy conservation and environmental preservation has further stimulated the development of terramechanics. In addition to being a good engineering design in the traditional sense, an off-road machine is now expected to attain a high level of energy efficiency and not to cause undue damage to the operating environment, such as excessive soil compaction in agriculture. Increasing activity in the exploration and exploitation of natural resources in new frontiers, including remote areas and the seabed, and the growing demand for greater mobility over a wider range of terrains and in all seasons have also given much new impetus to the development of terramechanics.
Chapter 1

Continuing interests of the USA, European Union and Russia, as well as programmes initiated by China, Japan, India and other nations, in the exploration of the Moon, Mars and beyond, have further stimulated advancements in terramechanics and its applications to the development of extraterrestrial vehicles, including manned and unmanned rovers (Wong and Asnani, 2008).

Terrain–vehicle mechanics is the prime subject of this book. It introduces the reader to the basic principles of terramechanics, which include the modelling of terrain behaviour, measurement and characterization of the mechanical properties of terrain pertinent to vehicle mobility, and the mechanics of vehicle–terrain interaction. As the performance of off-road vehicles over unprepared terrain constitutes a central issue in vehicle mobility, this book focuses on the study of vehicle–terrain interaction from the traction perspective. It provides the knowledge base for the prediction of off-road vehicle performance. Through examples, this book also demonstrates the applications of terramechanics to parametric analyses of terrain–vehicle systems and to the rational development and design of off-road vehicles from the traction perspective. The handling and ride of off-road vehicles are discussed in a separate book, Theory of Ground Vehicles (Wong, 2008).

1.1 Role of Terramechanics

The industries that manufacture and operate off-road equipment are multibillion dollar businesses. By considering the number of tractors and soil-cultivating implements used in agriculture, the number of earthmoving machines used in the construction industry, the number of off-highway trucks used in the off-road transport industry, and the number of combat and logistic vehicles used in the military, one can appreciate the scope for the applications of terramechanics.

Terramechanics, coupled with a systems analysis approach, can play a significant role in the development and evaluation of off-road equipment for a given mission and environment. Systems analysis is a methodology that provides a quantitative and systematic assessment of clearly defined issues and alternatives for decision makers. The knowledge of terramechanics can be applied, directly or indirectly, to the development, evaluation or selection of the following:

(a) vehicle concepts and configurations, defined in terms of form, size, weight and power;
(b) the running gear (or terrain-engaging elements) of a vehicle;
(c) the steering system of a vehicle;
(d) the suspension system of a vehicle;
(e) the power transmission and distribution system of a vehicle;

(f) the performance, handling and ride quality of a vehicle.

The role of terramechanics is illustrated in Figure 1.1.

There are many examples of the successful application of terramechanics and systems analysis methodology to the development and evaluation of off-road vehicles. One of the most striking examples is, perhaps, the development of the Lunar Roving Vehicle for the Apollo programmes under the guidance of Dr M.G. Bekker (1964, 1967, 1969, 1981). In a search for the optimum form of a vehicle for lunar surface exploration, walking machines, screw-driven vehicles, and a variety of tracked and wheeled vehicles were examined in detail (Asnani, Delap and Creager, 2009). Their performances were evaluated using the principles of terramechanics. The exhaustive studies led to the selection of a four-wheel vehicle with a unique type of tyre woven of steel wire and girded with titanium chevrons, as shown in Figure 1.2 (Cowart, 1971). It was found that this type of tyre produced optimum elasticity, traction, strength and durability with minimum weight, and was compatible with the vacuum and temperature extremes of the moon. This vehicle configuration was proved highly successful in operation on the lunar surface.

Another example of the application of terramechanics to the evaluation of terrain–vehicle systems was described by Sohne (1976) in connection with the studies of the optimum
configuration for agricultural tractors. Based on the principles of terramechanics, he performed an analysis of the drawbar pull–slip characteristics and tractive efficiency of five configurations ranging from rear-wheel-drive with front-wheel-steering to six-wheel-drive with four-wheel-steering, as shown in Figure 1.3. Based on the results of the analysis, a comparison of the technical as well as economic performance of the various configurations was made. This type of analysis provides the designer with quantitative information upon which a rational decision may be made.

More recent examples of the application of terramechanics principles and systems analysis methodology to the parametric evaluation of tracked vehicles were reported by Wong (1992a, 1995, 2007, 2008). Using a computer-aided method, known as NTVPM, the validity of which has been substantiated by field test data, the effects of tracked vehicle design on performance can be quantitative by evaluated.

Figure 1.4 shows the effects of the initial track tension coefficient (i.e. the ratio of initial track tension to vehicle weight) on the drawbar pull coefficient (i.e. the ratio of drawbar pull to vehicle weight) of three vehicle configurations on deep snow, designated as Hope Valley snow (Wong, 2007). The three tracked vehicle configurations Vehicle A, Vehicle A (6W) and Vehicle A (8W) with five, six and eight overlapping roadwheels, respectively, are shown in Figure 1.5. It shows that the initial track tension has a significant effect on soft ground mobility of tracked vehicles with different design configurations. This finding has led to the development of an innovative device—a central initial track tension regulating system. This remotely control device enables the driver to increase the initial track tension for improving
Figure 1.3: Comparison of various configurations for agricultural tractors (Reprinted by permission of ISTVS from Sohne, 1976)

Figure 1.4: Variations of the drawbar pull coefficient with the initial track tension coefficient for the three vehicle configurations at 20% slip on Hope Valley snow, predicted by the computer-aided method NTVPM
vehicle mobility on soft ground. This is analogous to the central tyre inflation system for improving wheeled vehicle mobility. The central initial track tension regulating system has been installed in a new generation of military vehicles (Wong, 1995). Figure 1.6(a) and (b) show the effects of the location of the centre of gravity (CG) and track width on the drawbar pull coefficient of Vehicle A, respectively, on Hope Valley snow (Wong, 2007). The analytical framework and the basic features of NTVPM are described in Chapter 7.

The computer-aided method NTVPM has been successfully used in the development of new products by off-road vehicle manufacturers and in the assessment of vehicle candidates from a procurement perspective for governmental agencies in Europe, North America, and Asia.

1.2 Some Basic Issues in Terramechanics

The study of the performance of a vehicle in relation to its operating environment — the terrain is a major focus in terramechanics. Accordingly, the modelling of terrain behaviour,
the measurement and characterization of terrain properties, the identification of pertinent parameters of the vehicle that affect its performance, and the elucidation of the interaction between the vehicle and the terrain are some of the basic issues in terramechanics. In the study of these issues, one should bear in mind that the prime objective is to provide the knowledge base upon which advancements in the design of off-road vehicles may be made.

1.2.1 Modelling of Terrain Behaviour

An understanding of terrain behaviour under vehicular load is of importance to the study of terramechanics. In the past, modelling the terrain as an elastic medium or as a rigid, perfectly plastic material has been widely used. Modelling the terrain as an elastic medium, together with the theory of elasticity, has provided a theoretical basis for the study of soil compaction. However, it is applicable only to dense terrain with vehicular load not exceeding a certain level. Modelling the terrain as a rigid, perfectly plastic material, together with the theory of

Figure 1.6: (a) Variation of the drawbar pull coefficient with the longitudinal location of the CG, and (b) variation of the drawbar pull coefficient with track width for Vehicle A at 20% slip on Hope Valley snow, predicted by the computer-aided method NTVPM
plastic equilibrium, has found applications to the estimation of the maximum traction of an off-road vehicle, to the prediction of the forces acting on a bulldozer blade, or to the assessment of tractive force developed by a lug (or grouser) of a wheel. However, it can only be applied to estimating the maximum force acting on a soil-engaging element that the terrain can support, but cannot be employed to predict terrain deformation.

In recent decades, attempts have been made to apply the concept of critical state soil mechanics to modelling terrain behaviour. It is based on the assumption that the terrain is homogeneous and isotropic. It has the potential of modelling terrain behaviour over a wide range of conditions, from the loose to the dense state. However, in many types of natural terrain encountered in off-road operations, they are seldom homogeneous or isotropic. As a result, the critical state soil mechanics has so far found few practical applications to the study of vehicle-terrain interaction in the field.

With the rapid advance in computer technology and computational techniques in recent years, it has become feasible to model the terrain as an assemblage of finite elements. However, some basic issues remain to be resolved, such as the development of a robust method for determining the values of the parameters of the finite element model to properly represent terrain properties. Furthermore, the finite element method is developed on the premise that the terrain is a continuum. Consequently, it has inherent limitations in simulating large, discontinuous terrain deformation that usually occurs in vehicle-terrain interaction. To study the interaction between a vehicle and granular terrain, such as sand and the like, the discrete element method has been introduced. While the discrete element modelling technique has certain unique features, several key issues remain to be resolved before it can be generally accepted as a practical engineering tool. These include the development of a reliable method for determining the values of model parameters to realistically represent terrain properties in the field. In addition, improvements are needed in computing technique for full-scale simulations of vehicle-terrain interaction, which would require millions of discrete elements to represent the terrain and lengthy computation even on supercomputers. The modelling of terrain behaviour is discussed in detail in Chapter 2.

In view of the limitations of the techniques for modelling terrain behaviour described above, to study vehicle mobility in the field, practical techniques for measuring and characterizing terrain properties are required.

1.2.2 Measurement and Characterization of Terrain Properties

Currently, the cone penetrometer technique, the bevameter technique and the traditional technique of civil engineering soil mechanics are used for measuring the mechanical properties of the terrain for the study of vehicle mobility in the field. The selection of a particular type of technique is, to a great extent, influenced by the intended purpose of the method of approach.
to the study of vehicle mobility. For instance, if the method is intended to be used by the off-road vehicle engineer in the development and design of new products, then the technique selected for measuring and characterizing terrain properties would be quite different from that intended to be used by the military personnel for vehicle traffic planning on a go/no go basis. Currently, there are two major techniques used in measuring and characterizing terrain properties for evaluating off-road vehicle mobility in the field: the cone penetrometer technique and the bevameter technique. These techniques are briefly reviewed below and are discussed in detail later in Chapters 3, 4, and 5.

A. Cone penetrometer technique

The cone penetrometer technique was developed during the Second World War by the Waterways Experiment Station (WES) of the US Army Corps of Engineers. The original intention was to provide military intelligence and reconnaissance personnel with a simple field device for assessing vehicle mobility and terrain trafficability on a ‘go/no go’ basis.

The cone penetrometer developed by WES has a 30-degree right circular cone with a 3.23 cm² (0.5 in²) base area (Figure 1.7). With the penetrometer, a parameter called the ‘cone index’ can be obtained. It represents the resistance to penetration into the terrain per unit cone base area. The index reflects the combined shear and compressive characteristics of the terrain and the adhesion and friction on the cone-terrain interface. However, the contributions of these factors cannot be readily differentiated. The cone index and its gradient with respect to penetration depth have been used as a basis for predicting off-road vehicle performance in fine-grained soil (clay) and in coarse-grained soil (sand), respectively.

Figure 1.7: The basic form of a cone penetrometer
While the cone index of a terrain can readily be obtained, the issue of whether it can be used to adequately identify terrain characteristics from the vehicle mobility or terrain trafficability viewpoint remains controversial. For instance, work by Reece and Peca (1981) indicates that while the cone index may be useful in identifying the shear strength of remoulded frictionless clay, it is inadequate for characterizing the properties of sand. Prompted by these findings, Turnage (1984) of WES reanalysed a sizable body of experimental data previously obtained. Based on the results of his re-examination, Turnage concluded that to achieve better accuracy in predicting tyre performance in a given sand with a particular moisture content, additional laboratory testing is required to define the relationship between the before-tyre-pass cone penetration resistance gradient and the corresponding relative density, compactability and grain size distribution. This implies that the original concept of using a simple, single cone penetrometer measurement to define the properties of coarse-grained soil has to be replaced by a series of extensive geotechnical testing and analysis, including in situ measurements, sample acquisition and laboratory testing.

B. Bevameter technique

The bevameter technique pioneered by Bekker (1956, 1960, 1969) is based on the premise that terrain properties pertinent to terramechanics can best be measured under loading conditions similar to those exerted by an off-road vehicle. A vehicle exerts normal and shear loads to the terrain surface. To simulate these, the bevameter technique comprises two separate sets of tests. One is a plate penetration test and the other is a shear test. In the penetration test, the pressure–sinkage relationship of the terrain is measured using a plate of suitable size to simulate the contact area of the running gear of a vehicle. Based on the measurements, vehicle sinkage and motion resistance may be predicted. In the shear test, the shear stress–shear displacement relationship and the shear strength of the terrain are measured, upon which the tractive effort–slip characteristics and the maximum traction of a vehicle may be estimated. To provide data for predicting the multipass performance of vehicle running gear and the additional vehicle sinkage due to slip, the response of the terrain to repetitive loading and the slip–sinkage characteristics of the terrain are also measured (Wong et al., 1984).

Figure 1.8 shows a vehicle-mounted bevameter in field operation. To facilitate the processing of terrain data, a portable, computerized data acquisition and processing system and the associated software have been developed and successfully used in the field (Wong, 1980; Wong et al., 1981). Figure 1.9 shows the system installed in a vehicle for field operation. The use of a computerized data acquisition and processing system not only greatly reduces the effort required to obtain and process the data but also makes it possible to employ more rational procedures for deriving the values of terrain parameters (Wong, 1980; Wong et al., 1982; Wong and Preston-Thomas, 1983a,b).

To reduce the uncertainty in extrapolating terrain data obtained in the field for use in the prediction of the performance of full-scale machines, the size of the test piece used in the bevameter measurements should be comparable to that of the contact area of a tyre or that of a track link.
For instance, measurements of the ground contact pressure under a track, shown in Figure 1.10, confirm that the idealization of a track as a strip footing is unrealistic, particularly for tracks with relatively short track pitch commonly used in high speed vehicles (Wong et al., 1984). The actual contact pressure under the track is not uniformly distributed, but rather is concentrated.
on the track links immediately under the roadwheels. This indicates that to better simulate track–terrain interaction, the size of the plate used in pressure–sinkage tests should be similar to that of a track link.

C. *Techniques used in civil engineering soil mechanics*

In civil engineering, the properties of soil are often described in terms of shear strength, shear modulus, density, void ratio, etc. To measure these parameters, soil samples are usually taken from the field and tested in a laboratory. The shear strength of the terrain is usually measured using a triaxial apparatus or a direct shear box.

The measurement of terrain properties in the field has certain advantages over that in the laboratory. The major advantage is that measurements are taken when the terrain is in its natural state, thus eliminating the possibility of disturbing the terrain samples during the sampling process for laboratory testing. Furthermore, field testing is generally less expensive and faster, particularly when a portable data acquisition and processing system is used.

As the procedures and facilities used in civil engineering soil mechanics are not particularly suited to the study of vehicle mobility in the field, they are only in limited use.

### 1.2.3 Modelling of Vehicle–Terrain Interaction

There are two prime objectives of the study of vehicle–terrain interaction. One is to establish the functional relationship between the performance of an off-road vehicle and its design.
parameters and terrain characteristics. These will enable the engineering practitioner to realistically predict vehicle performance under different operating conditions. An accurate method for predicting off-road vehicle performance is of prime interest to the designer, as well as to the user, of off-road vehicles. The other objective is to establish a procedure with which the changes in terrain conditions caused by the passage of an off-road vehicle or soil working machinery may be predicted. This is of great interest to the agricultural engineer in the evaluation of soil compaction caused by farm vehicles and to the construction equipment engineer in the assessment of the effectiveness of soil compactors and the like.

In this book, emphasis is placed on the discussion of the interrelationships between off-road vehicle performance and its design and operational parameters and terrain characteristics.

On a given terrain, the performance of an off-road machine is, to a great extent, dependent upon the manner in which the machine interacts with the terrain. Figures 1.11 and 1.12 show the flow patterns of soil under the action of a rigid wheel and of a wheel with grousers, respectively (Wong and Reece, 1966; Wong, 1967; Wu et al., 1984). As a result of the interaction between the machine element and the terrain, normal and shear stresses are developed on the machine–terrain interface. Figure 1.10 shows the variation of the normal pressure exerted by a flexible track on a snow-covered terrain. The normal and shear stress distributions on the contact area of a tyre in a sandy loam are shown in Figure 1.13 (Krick, 1969). It can be seen that in most cases the interaction between a machine element and terrain is very complex. For example, the flow patterns of soil under a wheel depend upon its kinematics as
defined by its slip, while the stress conditions at the interface are determined by terrain conditions as well as the design and operational parameters of the wheel, including its dimensions and the vertical load and torque applied to it.

Since the performance of an off-road vehicle, defined in terms of its motion resistance, tractive effort, drawbar pull, tractive efficiency, etc., is determined by the normal and shear stresses on the vehicle–terrain interface, a central issue in terramechanics is the formulation of a mathematical model to predict the interacting forces between the vehicle and the terrain, based on the knowledge of terrain behaviour and pertinent design and operational parameters of the vehicle.
Identifying the design parameters of the vehicle that significantly influence vehicle–terrain interaction is of importance in formulating a mathematical model for off-road vehicle performance. For instance, tyre diameter, section width, section height, and lug angle and spacing are considered to have varying degrees of influence on the tyre–terrain interaction. For tracked vehicles, design parameters, such as the number of roadwheels, roadwheel dimensions and spacing, track geometry and dimensions, initial track tension, suspension characteristics, and arrangements for the sprocket, idler and supporting rollers, are shown to have an effect on the tractive performance.

1.3 Approaches to Terramechanics

A variety of methods of approach to the study of off-road vehicle mobility has been developed over the years. They range from entirely empirical to highly analytical. The selection of the method of approach is greatly influenced by the following factors.

A. Intended purposes

Depending upon whether the method is to be used by the development and design engineer in the optimization of vehicle design, by the procurement manager in the evaluation of vehicle candidates for a given mission, or by the vehicle operator in assessing vehicle mobility on a ‘go/no go’ basis, the method of approach varies greatly. For instance, a method intended for use in the design and development of off-road machinery requires a level of sophistication, accuracy, and detail that differs substantially from that intended for use by military intelligence and reconnaissance personnel in evaluating vehicle mobility in the field.

B. Environmental, economic and operational constraints

As in any other branches of engineering, the method of approach to the study of vehicle-terrain interaction is subject to constraints. For instance, in the selection of the techniques for identifying the mechanical properties of terrain in remote areas, on the seabed, or on the surface of other planets, environmental, economic, operational and other constraints may be the most important factors to be considered.

Comparison and evaluation of different methods of approach to terramechanics should, therefore, be made in the context of their intended purposes and constraining factors.

1.3.1 Empirical Methods

It is generally recognized that the interaction between an off-road machine and the terrain is complex and difficult to model accurately. To circumvent this difficulty, empirical methods for the study of vehicle mobility have been developed.
Following the empirical approach, vehicles are tested in a range of terrains considered to be representative and at the same time the terrain is identified by field observations and simple measurements. The results of vehicle performance testing and terrain measurements are then empirically correlated. This can lead to the development of a scale for evaluating terrain trafficability on the one hand and vehicle mobility on the other. This approach is best exemplified by the work of the US Army Waterways Experiment Station (WES) based on the cone index. The method was first developed during the Second World War and was originally intended to provide military intelligence and reconnaissance personnel with a simple means to assess terrain trafficability and vehicle mobility on a ‘go/no go’ basis. Recently, this approach has been extended, for instance, to empirically correlate certain dimensionless performance parameters of tyres with mobility numbers (numerics) based on the cone index or the cone index gradient. Some success has been reported in applying this empirical method to the prediction of tyre performance on remoulded frictionless soils. However, difficulties have been encountered in the application of the method to the evaluation of tyre performance in certain types of sand, as reported by Reece and Peca (1981). It has also been reported by Gee-Clough (1978) that this empirical approach does not give sufficiently accurate predictions of certain performance parameters of tyres.

Within the context of their intended purposes, well-developed empirical methods are useful in estimating the performance of vehicles with design features similar to those that have been tested under similar operating conditions. It is by no means certain, however, that empirical relations can be extrapolated beyond the conditions upon which they were derived. Consequently, it is uncertain that an entirely empirical approach could play a useful role in the evaluation of new design concepts or in the prediction of vehicle performance in new operating environments. Furthermore, an entirely empirical approach is only feasible where the number of variables involved in the problem is relatively small. If a significant number of parameters are required to define the problem, then an empirical approach may not be cost effective.

To provide a more general approach to terramechanics, particularly for parametric analyses of terrain–vehicle systems, other methods of approach have been developed.

### 1.3.2 Computational Methods

With rapid progress in computer technology and the availability of commercial computer codes, the finite element method (FEM), and the discrete (distinct) element method (DEM) have been introduced into the analysis of vehicle-terrain interaction. These methods generally involve intensive computation and may be referred to as computational methods. They have the potential of providing a tool with which certain aspects of the mechanics of vehicle-terrain interaction may be examined in detail.

Based on a review of the state-of-art in the applications of these computational methods to the study of vehicle-terrain interaction, it appears that the finite element method or the discrete element method may be applied to evaluating, on a relative basis, the design and performance of
tyres or soil engaging implements of simple form. Predictions of tyre performance based on these methods have been shown to be in qualitative agreement with experimental data on certain types of terrain (Liu and Wong, 1996; Seta et al., 2003). For a track system which is a complex mechanical system, its interaction with the terrain involves not only the part of the track system in contact with the terrain, but also other factors, such as roadwheel system configuration, suspension characteristics, locations of the sprocket and idler, initial track tension, arrangements for the supporting rollers on the top run of track, etc. To make the analysis amenable to the finite element method, however, the track usually has to be simplified as a rigid footing with either uniform or trapezoidal form of normal pressure distribution (Karafiath, 1984). In many cases, the ratio of the shear stress to normal pressure has also to be specified at the outset of the prediction process. It will be shown later that these are unrealistic. Consequently, it cannot provide the off-road vehicle engineer with a realistic tool for design and performance evaluation of track systems. Furthermore, as pointed out previously, the finite element method is based on the premise that the terrain is a continuum. As a result, it has inherent limitations in simulating large, discontinuous terrain deformation which often occurs in off-road operations.

Several other issues must also be resolved before these computational methods can be considered as a practical engineering tool. These include the development of a robust method for determining the values of the parameters in the finite element or discrete element method that realistically represent the mechanical properties of the terrain in the field. This poses one the greatest challenges, in view of the variability and complexity of terrain behaviour in the natural environment. Furthermore, it is estimated that to conduct a realistic three-dimensional simulation of full-scale machine-terrain interaction problem by the discrete element method, the number of elements required would be in the order of $10^6$ to $10^8$. This would require high-power computing resources, usually supercomputers. For instance, it has been shown that in a simulation of the interaction between a mine plow and soil, ten million elements are used and the simulation takes just over 16,000 CPU hours on a 256-processor Cray T3E supercomputer (Horner, Peters and Carrillo, 2001).

In summary, the applications of the finite element method or the discrete element method to the study of vehicle-terrain interaction are still in the nascent stage. Prior to being considered acceptable as a useful tool for design and performance evaluation of off-road vehicles, several challenging issues facing these computation methods have to be resolved, as outlined above.

Detailed discussions of the finite element method and the discrete (distinct) element method and their applications to vehicle mobility study are presented in Chapter 2.

### 1.3.3 Methods for Parametric Analysis

In view of the limitations of the empirical and computational methods noted above, mathematical models for parametric analysis of the performance of off-road vehicles have been
developed. A pioneering effort in this area was made by Bekker (1956, 1960, 1969). Lately, a series of computer-aided methods for parametric analysis of the performance and design of both tracked vehicles and off-road wheeled vehicles, from a traction perspective, have emerged (Wong, et al., 1984; Wong and Preston-Thomas, 1986 and 1988; Wong, 1992; Gao and Wong, 1994; Wong, 1995, 1998, 2007, 2008; Wong and Huang, 2005, 2006a and b, 2008). These include methods for performance and design evaluation of vehicles with flexible tracks (NTVPM), vehicles with long-pitch link tracks (RTVPM), and off-road wheeled vehicles (NWVPM). The basic features of NTVPM, RTVPM and NWVPM are presented in Chapters 8, 10 and 12, respectively.

These methods are based on an understanding of the physical nature of vehicle-terrain interaction and on the principles of terramechanics. They take into account all major design features of the vehicle that affect its performance. All pertinent terrain characteristics, such as pressure-sinkage and shearing characteristics and response to repetitive loading, measured by the bevameter technique (Bekker, 1960, 1969; Wong, 2008) are taken into account. The predictive capabilities of these computer-aided methods have been verified by field test data obtained on various types of terrain.

These computer-aided methods are particularly suited for the evaluation of competing designs, optimization of design parameters, and selection of vehicle candidates for a given mission and environment. They have been successfully used to assist off-road vehicle manufacturers in the development of new products and governmental agencies in the evaluation of vehicle candidates in Europe, North America, Asia and Africa. Examples of the applications of NTVPM, RTVPM and NWVPM to performance and design evaluations are presented in Chapters 9, 10 and 12, respectively.

In summary, the introduction given above indicates that since the founding of terramechanics in the 1960s, a great deal of progress has been accomplished. A number of outstanding examples have demonstrated its relevance to engineering practice and its growing acceptance in industry. With the continual enthusiasm shown by an increasing number of countries in exploration on the surfaces of the Moon, Mars and other planets, terramechanics is playing an increasingly significant role in the development of the mobility systems of extraterrestrial rovers (Wong and Asnani, 2008). Figure 1.14 shows the image of the NASA Mars Exploration Rovers (Spirit and Opportunity) launched from earth in the middle of 2003 and landed on Mars in early 2004.

Looking ahead, it appears that terramechanics has to provide an improved knowledge base for the further development of engineering tools for performance and design evaluation of off-road vehicles operating in a wider spectrum of environment, and with greater accuracy and reliability. In addition, these tools have to be user-friendly that will appeal to a wide range
of engineering practitioners, including vehicle designers, researchers and procurement managers. In the further development of terramechanics, one should bear in mind that the prime objective is to provide the engineering practitioner with useful and reliable tools that will lead to innovations in the design and development of off-road vehicles to meet society’s changing needs for environmental protection, energy conservation and sustainable development.