RECOMMENDATION OF A NEXT GENERATION TERRAMECHANICS EXPERIMENTATION CAPABILITY FOR GROUND VEHICLE SYSTEMS

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Abstract

This paper presents a review of literature for a terramechanics experimentation capability for the U.S. Army Tank Automotive Research, Development, and Engineering Center (TARDEC) in Warren, Michigan. Despite the increasingly important role that light-weight and small ground vehicles play in combat and military operations, most researchers do not currently have the ability to (i) measure vehicle operational parameters such as forces, torques, and sinkage that a wheel or track on a vehicle experiences, (ii) investigate the interaction that occurs between a wheel/track and soft soil, and (iii) objectively determine a light-weight or small vehicle's ability to navigate complex off-road terrain. As a consequence, researchers currently evaluate the performance of a light-weight vehicle using semi-empirical techniques that were originally derived for heavy vehicles. The goal of this paper is to research the next generation terramechanics experimentation capability that will enable the exploration and validation of mobility models for wheel/tracked/legged robots. The recommended system will also facilitate an investigation of scalability of mobility performance between small and large systems. The recommendation of this facility draws on literature reviews of current facilities around the world, sophisticated measurement techniques, and modeling techniques. The recommended terramechanics experimentation capability will invigorate in-house research, enable collaborative relationships with other government agencies, academia, and industry, and encourage the investigation of unexplored terramechanics phenomena.

Keywords: terramechanics, experimentation, recommendation, next-generation

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1 Background

Despite the increasingly important role that light-weight and small ground vehicles play in combat and military operations, most researchers do not currently have the ability to (i) measure vehicle operational parameters such as forces, torques, and sinkage that a wheel or track on a vehicle experiences, (ii) investigate the interaction that occurs between a wheel/track and soft soil, and (iii) objectively determine a light-weight or small vehicle's ability to navigate complex off-road terrain. In 1945, TARDEC established the Land Locomotion Laboratory (LLL) and hired M. Gregory Bekker to lead it. Whereas the movement of ships through the water and aircraft through the air could be approached theoretically, no theory existed to describe the movement of off-road vehicles across the terrain. So began a world-renowned effort to describe vehicle terrain interactions [1].

Figure 1: *Land Locomotion Laboratory [1].*

The Land Locomotion Laboratory was organized by the U.S. Army Ordnance Corps in 1954 with the initial mission of studying the problem of mud mobility. The beginning laboratory staff was as small as the mission was large since it consisted of Dr. M. G. Bekker, who was at the time a Lieutenant Colonel in the Canadian Army on loan to the U.S. Army. A staff was gradually built up for the laboratory with Bekker providing technical guidance and inspiration for the organization. In early 1957 the laboratory staff was augmented with six engineers who came to the United States from Hungary. The current staff consists of eleven engineers supported by technicians, machinists, and clerical personnel.

The mission of the laboratory was quickly modified from the study of mud mobility, or, more correctly, immobility, to the study of vehicle performance under adverse terrain conditions. The use of the term "terrain" demanded consideration of a broad range of problems including soft soil, rough surfaces, vegetation, severe slopes and pitches, and inland waterways. An overall view of the laboratory is shown in **Figure 1**.

Figure 2: *Ride characteristic vehicle analog model facility [1].*

The large soil bins, such as the one shown in Figure 2, were approximately 100 ft. long, 12 ft. wide, and 5 ft. deep. A hydraulic drive system installed on the bins permitted the application of a 6000 lb. drawbar load or provides a driving force of 6000 lb. The hydraulic drive was connected to a chain drive system to which dynamometers or soil processing equipment could be attached. The maximum speed provided by the drive system was 10 ft./sec. The design objective was to provide as flexible a facility as possible permitting the testing of single wheels or complete track suspensions. The dynamometer is designed so that the wheels or tracks could be either driven or towed. The track test permitted variation of drive sprocket location, road wheel size and spacing, number of road wheels, track tension, spring and damping rates and track width. Additionally, the laboratory had a respectable collection of standard soil test equipment such as the triaxial machine and shear box to identify soil. Lastly, the laboratory had several field testing devices, such as the Polecat with a field Bevameter on the powered trailer, shown in **Figure 3**, which enabled the recording of terrain profiles with high accuracy.

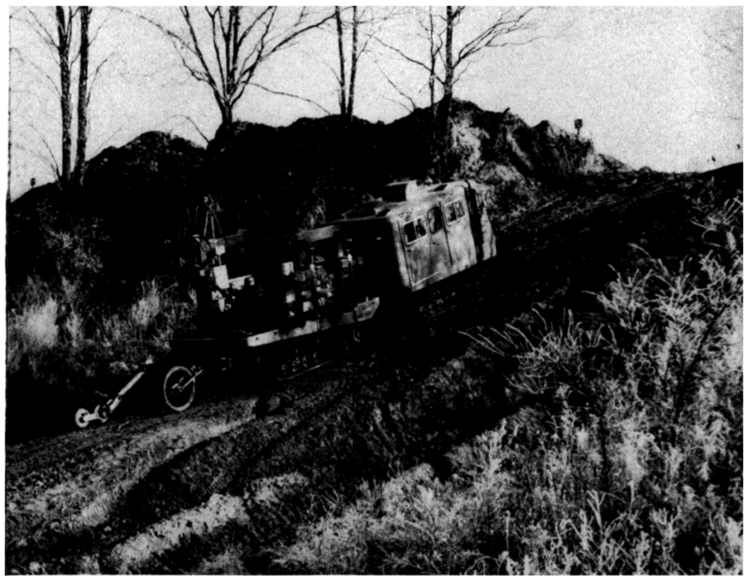

Figure 3: *Polecat with a field Bevameter on the powered trailer [1].*

2 Motivation

The goal of this paper is to research the next generation terramechanics experimentation capability that will enable the exploration and validation of mobility models for wheel/tracked/legged robots. Due to these unique requirements, it is essential to be able to experimentally evaluate the off road vehicle performance over a wide range of vehicle classes and terrain types. A review of the Journal of Terramechanics yielded several facilities around the world that have capabilities in terramechanics experimentation, shown in **Figure 4**. Despite this large array of facilities, there remains a lack of understanding of key terramechanics phenomena, such as moisture effects, velocity effects, and scaling, due to the limitations in current experimental capabilities.

Figure 4: *Terramechanics experimentation facilities around the world.*

2.1 Moist Soil

Whenever a load is a applied to a terrain, the stress level within a certain boundary of the terrain may reach a limit at which any small increase of stress produces a rapid increase of strain, which results in material failure [2]. Depending on the moisture content of the soil, adhesive and cohesive forces can play a large role in this failure, resulting in a highly complex mechanical structure of the soil [3]. The addition of a small amount of liquid to a soil can cause the particles in the soil to agglomerate, which may weaken or strengthen the terrain [4].

Moist soils are very common and exist in a variety of applications, such as manufacturing, agriculture, military, and rescue operations. In manufacturing, for instance, liquid spraying is of importance in flotation, coating, flocculation, granulation and drying. In these operations, liquid transfer between particles plays the central role, whereby wetting, rewetting and mixing all take place simultaneously. A better understanding of liquid transfer between particles during flow can aid in the control of these processes [5]. In agriculture, puddling is the most common land preparation method used for wetland production of rice in Asia. Puddling is done by tilling the top 10-15 cm of soil at a moisture content above field capacity until most aggregates are destroyed and the soil is transformed into a slurry [6]. Highly saturated soils offer little resistance to tractor sinkage and can only support small drive-wheel tractive forces. The cage wheel-blocking problem, a condition shown in **Figure 5** where the wheel becomes completely laden with soil, is commonly encountered during wetland operations. During the laboratory studies on cage wheel lugs they found that soil adhesion plays a significant role for soil sticking on cage wheel lugs that ultimately results in cage wheel blocking [7]. On the other hand, the weakened soil caused by high saturation is the main factor which causes the wheel to slip, sink and remain standstill. For example, the wet soil caused by the tsunamis in Japan blocked rescue vehicles from saving life and provide disaster relief [8].

Figure 5: *Tractor immobilized due to cage wheel blocking [9].*

Although many researchers have studied the effect of various dry land operating regimes, there is little experimental and modeling work done for moist soils [10]. A lack of knowledge of moist soil mechanics from one side and limitations in developing real tests and collecting experimental data at desirable conditions from the other side have slowed down any new development in this area [11]. Despite few studies, moist soils are affected by several factors, including: volume changes associated with suction or saturation changes, shear strength effects associated with suction or saturation changes, and hydraulic behavior associated with suction or saturation changes. Some soils expand upon wetting, some collapse and some do both depending on the stress level [12].

2.2 Velocity Effects

Much of the current terramechanics investigations and theories apply to vehicles travelling at low speeds [13]. However, in almost every application of terramechanics, vehicles must operate at high speeds. In fact, energy loss due to erroneous management of agricultural tires was reported to be about 575 million liters per year in USA [14]. Typically, the effects of high speed are neglected [15]. Quasi-static modeling of soil-tool interaction is acceptable for the low speed range; however, considerable dynamic effects on soil can be produced by vehicles operating at high speeds, so that dynamic components must be incorporated in analytical models [16]. Tillage operations are usually carried out at low speeds, largely because to disturb large masses of soil demands high draught forces from tractors. High-speed tillage operations allow the farmer to increase machine work rates and get the field operations done in a timely manner [17]. Although, most test work has been for the study of the performance of terrain vehicles such as trucks, jeeps, tanks, and agricultural tractors [18], provisions must be made for sufficient power to overcome drag and provide capability for takeoff of aircraft on rough landing zones.

All-weather combat vehicles and robotics capable of higher-than-traditional off-road velocities are of interest, and it is instructive to determine the relationship between velocity and drag in a range lower than found in aircraft take-off velocities. Furthermore, for military computer simulations to become more accurate in predicting vehicle movement across varied terrain there is a need for better rolling resistance characterizations at ground vehicle speeds [19]. The variability of soil conditions influences the forces acting on the wheel and results in changes in wheel velocity and slip. In order to control off-road vehicle performance, such as applying a certain drawbar pull or operating within a defined traction efficiency range, a model capable of dealing with dynamically varying velocity is needed [20].

2.3 Scaling

The past few years have seen growing evidence that the principles of scaling have a useful application in soil mechanics research, with applications in vehicle mobility, agricultural tool draft, and earthmoving. Model testing is most attractive when the problem is not well enough understood to permit much headway by mathematical analysis, and when the testing of full-scale equipment is either impossible, or expensive, or unsatisfactory for some other reason [21]. These problems can be investigated by experiments using model working elements made to a reduced scale which can be operated in laboratory soil tanks in which the soil conditions can be carefully controlled and are not dependent on outside climatic conditions. The difficulties encountered in conducting full scale field tests have emphasized the need for scale model experiments in indoor soil tanks and this in turn has drawn the attention of workers in this field to model testing techniques used in many other branches of science [22].

Scaling analyses have been used in a variety of terramechanics applications. Designs of earth anchors, or devices that enhance the resistance with which the vehicle can derive from the ground during winching, have been compared using scaling principles [23]. Additionally, scaling has been used to simulate low gravity for the mobility of micro lunar rovers [24]. Similarly, bucket wheel devices were investigated for small scale lunar excavation missions [25].

3 Literature Review

A literature review was performed to understand how various terramechanics phenomenon are being studied, the techniques that are being used to model these phenomena, and the experimental testing methods and facilities that are being used to capture these phenomenon and validate these models.

3.1 Existing Terramechanics Experimental Facilities

Terramechanics is a subject that combines theories and experiments closely. Facilities around the world use a variety of experimental setups and high-performance sensors to investigate and validate terramechanics research. These facilities use the experimental results for several purposes: analyzing the performance of current vehicles, verifying newly developed technologies, and improving terramechanics models.

Asian Institute of Technology

Validation experiments were conducted under controlled conditions in a narrow laboratory soil bin at the Asian Institute of Technology. The experimental test rig, shown in **Figure 6**, included a narrow soil bin frame, a rigid wheel, a vertical loading shaft, a displacement transducer, and a load cell. The narrow soil bin was specially fabricated for the validation studies at the Agricultural Research Laboratory, Asian Institute of Technology, Thailand. A load cell of 0.981 kN maximum load, was used to measure the horizontal draft force caused by the soil particles on the rigid wheel during the validation test runs. The load cell was placed just above the rigid wheel and was fixed to the vertical shaft which held the rigid wheel. [26].

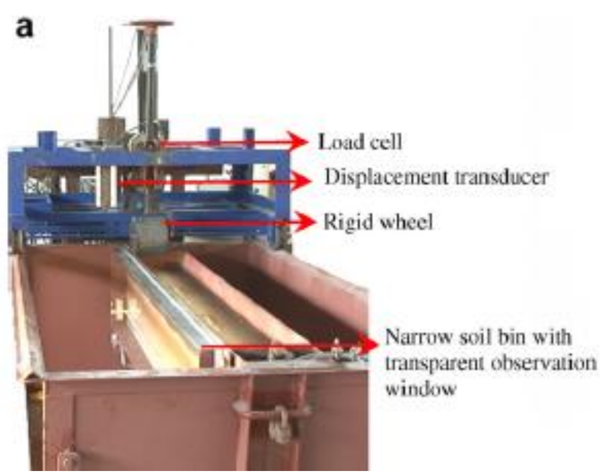

Figure 6: *The experimental test rig at AIT [26].*

Carnegie Mellon University

The experimental apparatus at Carnegie Mellon University consists of a glass-walled soil bin filled with relevant regolith simulant, an implement (wheel, excavation bucket, etc.), an actuated horizontal axis of motion and a high-speed camera, shown in **Figure 7**. When the implement module is equipped with a wheel, its rotations are position or velocity controlled in coordination with the horizontal axis to create a commanded, constant slip as the wheel travels forward. A linear rail allows the wheel to translate freely in the vertical direction allowing for natural sinkage to occur. This also allows for the transmission of a deadweight normal payload to be applied to the wheel. When the implement module is equipped with an excavation bucket, the vertical rail is locked and the rotary actuator is removed. A 6 DOF force/torque sensor is incorporated to measure the reaction loads in all directions. Sinkage is also measured via an optical encoder affixed to the vertical free linear axis. All telemetry; wheel angular velocity, travel velocity, slip, sinkage, load and power are logged simultaneously at 20Hz or higher. A digital SLR camera with a 50mm macro lens is used to image the soil where it interfaces with the test implement, logging frames simultaneously with the rest of the telemetry [27].

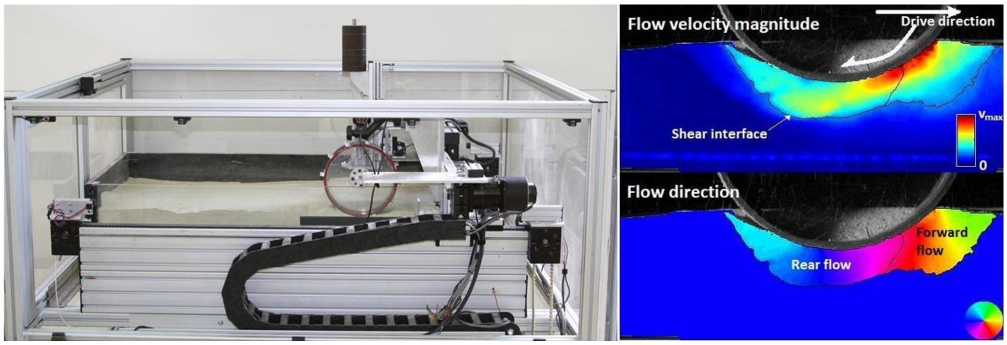

Figure 7: *Glass-walled soil bin at CMU with horizontal axis of motion (left) and sample processed output for driven wheel [27].*

German Aerospace Center

Two different test beds at the German Aerospace Center, one dedicated to single-wheel characterization and another one for rover system-level locomotion performance evaluation, were used as shown in **Figure 8**. Both test beds feature soil bins filled with appropriate Martian soil simulant. The main tested purpose is to measure vehicle tractive ability (i.e. drawbar pull) on homogeneous surfaces and under controlled conditions. As a result, several distinct modifications into previous terramechanical wheel-soil models were introduced, relating primarily to modelling of slip-sinkage behavior [28].

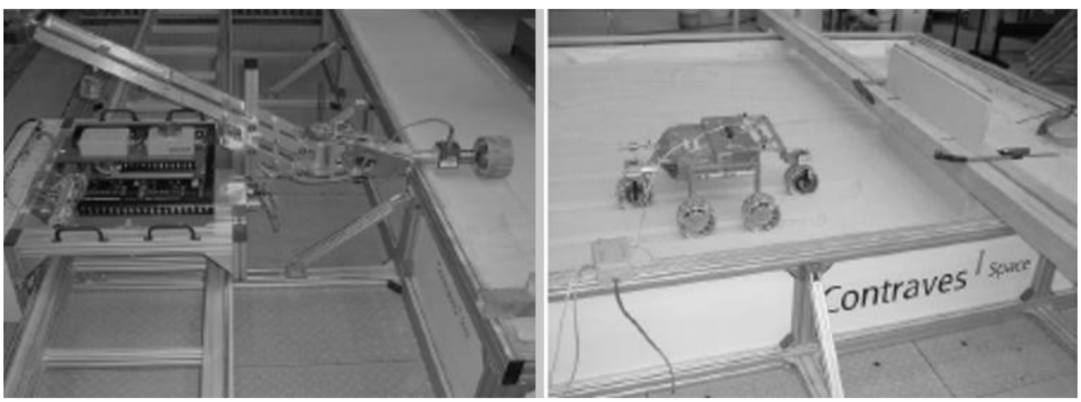

Figure 8: *RCET single-wheel tested (left) and system-level tested at DLR [28].*

Harbin Institute of Technology

The wheel-soil interaction test system, shown in **Figure 9**, was developed at the Chinese State Key Laboratory of Robotics and System, Harbin Institute of Technology. The test bed has dimensions of 1700mm x 850 mm x 900 mm. It can be used to perform experiments on wheels with a radius ranging from 50 mm to 200 mm and a width ranging from 60 mm to 300 mm. The test bed contains three motors (driving motor, steering motor, and carriage motor), instrumented with a displacement sensor, six-axis F/T sensor, driving torque sensor, current sensors, and optical encoders. The driving motor can cause the wheel to move forward. The carriage motor is used together with a conveyance belt that imitates the influence of the vehicle body on the wheel in order to create various slip ratios. The steering motor can drive the motor to steer. The wheel sinkage is measured by a high-precision linear-potentiometer displacement sensor. An F/T sensor can measure the drawbar pull, steering torque, side force, normal force, etc., while the driving torque of a motor is measured by a torque sensor. The current sensors and optimal encoders are used to measure the current and position of each motor [29].

Figure 9: *HIT wheel-soil interaction tested [30].*

Illinois Institute of Technology

Figure 10 shows the single-wheel tested at the Illinois Institute of Technology used to evaluate wheel sinkage for small wheel loads and diameters. The rigid, grouser-less wheel and carriage are driven independently. The wheel is also free to move vertically. By driving the wheel and carriage at different speeds, a full range of slip ratios can be attained. The soil bin walls must not interfere with the distribution of stresses beneath the wheel, which is dependent on the soil type, wheel dimensions and normal load. For the work contained within this paper, particular attention was paid to the depth requirement for dry sand [31].

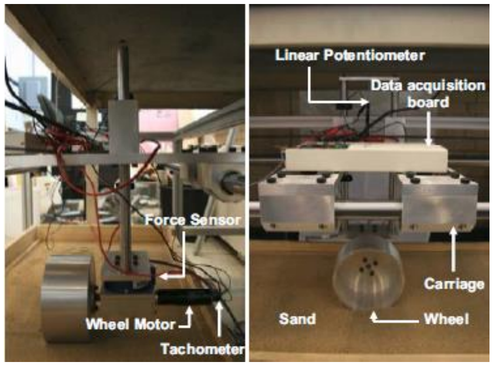

Figure 10: *IIT wheel-terrain tested [31].*

The tested utilizes three types of sensors to record performance data: 1) A six axis force-torque sensor, 2) a linear potentiometer and 3) tachometers attached to both the pulley and wheel motors. The force torque sensor, measuring wheel-soil interface loading, is rated to 200 N of axial loading and 20 Nm of torque. A linear potentiometer is used to measure displacement in the vertical direction, yielding sink- age data. Both acquisition of sensor data and motor control are performed using LabView [32].

Japan Aerospace Exploration Agency

A sloped mobility test bed, consisting of a wide soil bin with effective inner dimensions of 1.5 m (width), 2.0 m (length), and 0.2 m (depth), which could be tilted, was constructed at Chofu Aerospace Center (CAC), JAXA. The soil bin is axially rotated using a linear electrically driven actuator. A horizontal frame for carrying the wheel was constructed over the sloped soil bin. A target wheel attached at the end of a parallel link mechanism can freely sink vertically, with its weight controlled by the counterweight. Another counterweight is adjusted to counteract the motion resistance of the system carrier so that the applied drawbar condition can be controlled properly. A six axis force sensor monitors the motion resistance by measuring the horizontal reaction. The vertical sinkage of the wheel is measured indirectly with a rotation angle sensor as the difference in the angle at the hinge point of the parallel link mechanism. Finally, a laser distance sensor monitors the horizontal travel distance of the wheel [33].

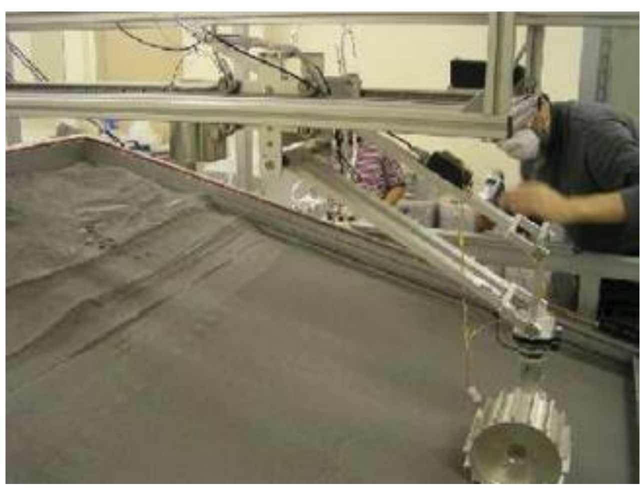

Figure 11: *View of the soil bin and single wheel dynamometer [33].*

Massachusetts Institute of Technology

The Massachusetts Institute of Technology (MIT) Field and Space Robotics Laboratory's Wheel-Terrain Characterization Testbed consists of a wheel carriage that can translate both horizontally and vertically, shown in **Figure 12**. Potentiometers sense carriage motion. A torque sensor and motor are attached to the wheel and a force/torque transducer is located on the wheel carriage above the wheel. Controlling the translational velocity of the wheel carriage and the angular velocity of the wheel enables one to control the slip ratio. With this setup, the wheel-soil interaction forces and torques (and the corresponding slip ratio) can be measured [34].

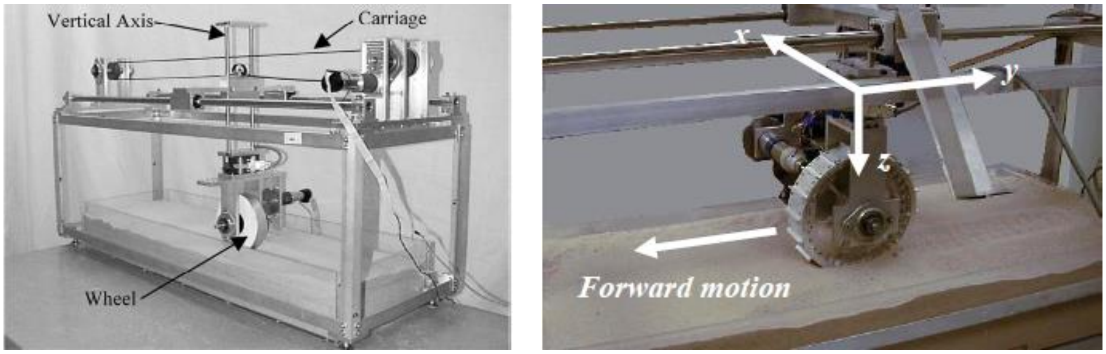

Figure 12: *MIT terrain characterization tested [35].*

The carriage linear velocity is computed from the carriage pulley angular velocity. The vertical wheel sinkage is measured with a linear potentiometer. The drive motor current is estimated by measuring the voltage across a current-sense resistor. The six-component wrench between the wheel and carriage is measured with a six-axis force/torque sensor. The force sensor allows measurement of the normal load and drawbar pull. The prediction algorithm is run on an Intel 486 66 MHz processor at a rate of 250 Hz [35].

Tohoku University

Figure 13 shows the overview and schematic view of the single-wheel test bed at Tohoku University. The test bed comprises both a conveyance unit and a wheel-driving unit. The steering angle, which is equivalent to the slip angle in this test bed, is set between the conveyance unit and the wheel. The translational velocity and angular velocity of the wheel are calculated based on the data obtained by the encoders that are mounted on the conveyance motor and wheel-driving motor, respectively. The forces and torques generated by the wheel locomotion are measured using a six-axis force/torque sensor located between the steering part and the wheel. The wheel sinkage is measured by using a linear potentiometer. A wheel with a diameter of 0.18 m and a width of 0.11 m is covered with paddles having heights of 0.01 m. The load of the wheel is approximately 6.6 kg [36].

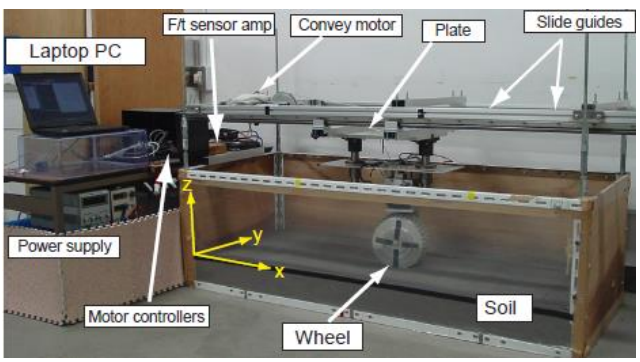

Figure 13: *Tohoku University's single wheel tested [36].*

A sandbox, shown in **Figure 13**, with dimensions of 1×2 m is used for the experiment. The sandbox contains a 15 cm thick layer of Toyoura standard sand (JIS R 5201); which has very low viscosity and a uniform particle size. The sandbox can be tilted manually up to 20 degrees. Additionally, a four-wheeled robot can be driven independently on the soil bin, shown in **Figure 14**. The motion measurement system uses telecentric optics in order to measure the robot velocity without using external devices embedded in the target environment [37].

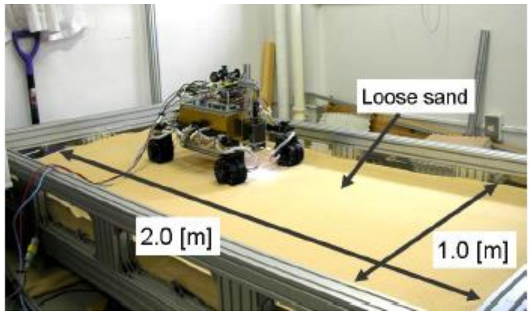

Figure 14: *Tohoku University's experimental setup and rover tested [37].*

Virginia Polytechnic Institute and State University

The main test platform for investigating the tire-soil interaction for model validation is the Terramechanics Rig in the Advanced Vehicle Dynamics Lab at Virginia Tech. This single-wheeled test rig essentially simulates a rigid-suspension, quarter-car model made to extensively investigate tire dynamics when applied to a wide variety of terrains, as shown in **Figure 15**. The rig is driven by two motors - one provides the longitudinal velocity of the test wheel by actuating the belt system which moves the carriage along the test terrain, and the second motor controls the angular velocity of the test wheel; thus, allowing the user to predefine the different longitudinal slip test scenarios . The rig takes measurements via the Kistler P650 wheel hub sensor, which measures all three forces and moments attributed to the tire-soil interaction, wheel rotation, and angular velocity, also a string potentiometer is used to measure the wheel vertical travel [38].

Figure 15: *Virginia Tech's terramechanics rig [39].*

3.2 Studies of Specific Terramechanics Phenomena

To better understand how researchers use experiments to study terramechanics, several specific phenomena were chosen that are relevant to military applications. These specific phenomena include: moisture effects, velocity effects, and scaling. Within each phenomena, the experiments were classified as one of three different tests. An experiment that attempts to determine the bulk material properties on a sample of soil is considered a material test. An experiment that takes place in actual situations reflecting intended use is classified as a field test. Lastly, an experiment that isolates specific terramechanics phenomena and reduces experimental variability by better control soil and machine parameters is classified as a controlled test.

Moisture Effects

The amount of moisture that a sample of soil contains is considered a state of the soil. All soils can be partially saturated with water, and it is safe to state that military vehicles must traverse a large range of moist soils [12]. The location and movement of water in a soil depends on several factors, including the porosity, gravity, mass flow, and capillary action occurring in the soil matrix. Capillary action is defined as the natural movement of water due to the attraction to solids (adhesion) and attraction to other water molecules (cohesion) and is counterbalanced by the effects of gravity and air pockets [40]. Understanding moist soil is of great importance to terramechanics because it was found that depending on the amount of water present in the soil, the trafficability of wet sand can be better than dry sand. At a certain saturation state, however, the soil will become a mud resulting in low shear forces and a higher chance of soil sticking to the wheel [8]. There are several different types of tests that are used to study moist soil; these include material tests, field tests, and controlled tests.

Material Tests

Examples of material tests in moist soil studies include determining the shear parameters of a sample of moist soil using either the triaxial apparatus or the translational shear box [2], [41]. In shear tests, a shear ring is employed to apply shear loading to the terrain surface under various normal pressures. The torque applied and the resulting angular displacement of the shear ring are recorded from which the shear stress-shear displacement relationship and the shear strength parameters of the terrain can be derived. Another material test studied the changes in pore water pressure as a function of initial soil water content and applied stress by compressing a sample of wet soil in a cylindrical device that hydraulically controlled the applied pressure. The applied pressure and the resulting sinkage of the plate are recorded [42]. When the level of saturation is important, several techniques are used to control the moisture content. One such technique is the capillary method, which completely dries the soil samples before putting them into a tray of water to allow the soil to absorb the moisture through capillary forces [40].

Field Tests

One of the most common field tests is the bevameter technique which comprises two basic sets of tests: one is a set of plate penetration tests, and the other is a set of shear tests. The difference between the bevameter and other material tests is that the bevameter takes measurements in the actual soil, rather than a laboratory sample. A hydraulic ram is usually used to apply normal load to the sinkage plate in the pressure-sinkage test [2].

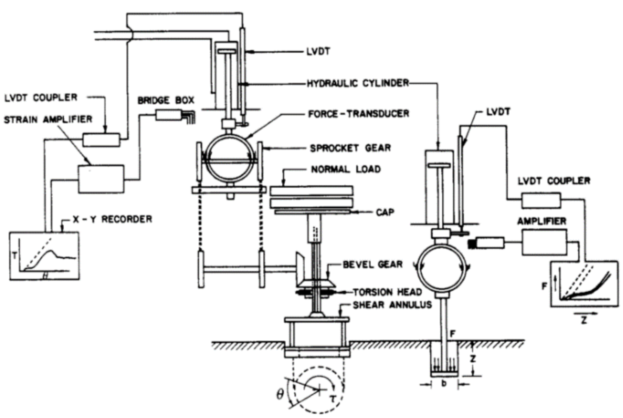

Figure 16: *Schematic view of the bevameter apparatus [43].*

To study the influence of different combinations of external load and soil water on soil compaction, a field test was conducted at the Agricultural Experiment Station at the Sultan Qaboos University, Oman [44]. Four soil water contents and four external loads were used in a complete factorial experiment by adding water to an agricultural plot using water tankers and driving over the plots using several different tractors to compact the soil at different external loads. Despite the large amount of variability in these experiments, the researchers were able to statistically show that both soil water and external load significantly affected soil compaction as measured by soil bulk density, soil strength, and soil water infiltration rate.

Controlled Tests

Soil-wheel interaction tests are conducted in fields for development of a prototype machine or evaluations of an existing machine, so that the tests could emulate the actual situation. Compared to the test in the actual field, soil bins provide several benefits to soil-wheel interaction studies. The tests can be conducted all year round without weather interruption. Soil bins also allow researchers to control soil type. For example, to study the performance and investigate a DEM model of a single-wheel travelling over wet sand and mud, researchers at the University of Science & Technology used a narrow laboratory soil bin [8], shown in **Figure 17** and **Figure 18**.

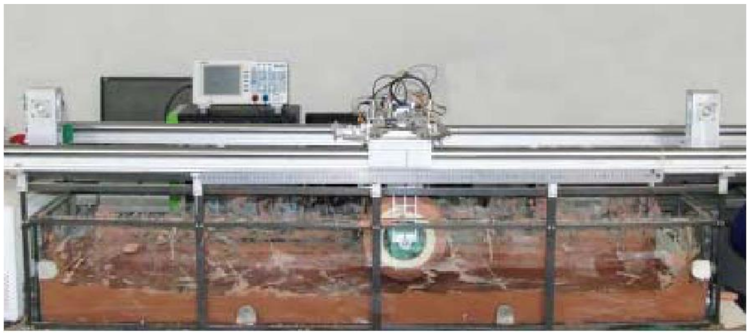

Figure 17: *Wheel-soil interaction tested [8].*

Soil bins have also been used at the Safiabad Agricultural research center to study the energy requirements of a tillage tool operating through clay loam soil with varying moisture contents. Similar tools were used in the instrumented soil bin in the Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Canada, that is 1.8 m wide and 12 m long with an effective length of 9 m [11]. Additionally, laboratory soil bins were used to study the effect of surface coating on lug forces to prevent cage wheel blocking [7].

Figure 18: *Traces of wheel in wet sand (up, with s=0, 15, 50%) and mud (0, 10, 20%) [8].*

Lastly, a transparent soil bin was used to observe the deformation pattern caused by lug sinkage and slip of a wheel. The experiments were conducted in a glass sided laboratory soil bin using Bangkok clay soil. A glass window of 100 x 40 cm was provided on one side of the soil bin. After the desired moisture content and cone index were reached, white dots of 1.5 mm diameter were marked on the soil surface in the window area to track how the clay soil deformed [9], shown in **Figure 19**.

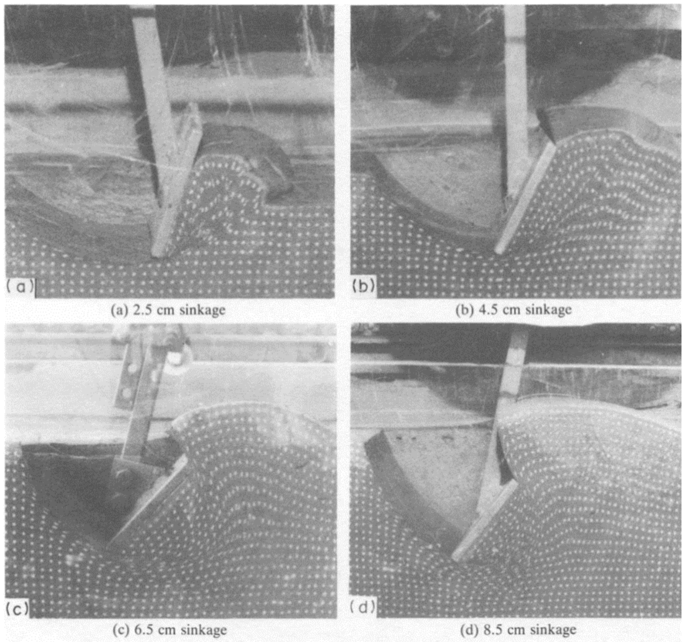

Figure 19: *Soil deformation pattern at 30 degree lug rotation and 50% slip at various lug sinkage values: (a) 2.5 cm sinkage; (b) 4.5 cm sinkage; (c) 6.5 cm sinkage; (d) 8.5 cm sinkage [9].*

Velocity Effects

Most of the published data in terramechanics are from experiments performed at relatively low speeds, up to 3 m/s. Experimental results cannot be directly extrapolated for draft at higher speeds. Military maneuvers are seldom run at the low velocities seen in most terramechanics experiments. When vehicles are rolling on soft terrain, the impact on the soil is dependent on the rolling speed [45]. Even when the device is driven at a steady speed, irreversible and transient phenomena may occur. Inertial forces have remarkable importance for sandy, frictional soils. In clay soils the draft required is generally not sensitive to inertial forces, but shear strength increases substantially with increasing shear rates [16].

Material Tests

Material tests are commonly used to determine the effect of velocity on different soil parameters. To determine the effect of penetration rate on soil sinkage, pressure-sinkage tests were carried out at constant penetration velocities ranging from 2 to 80 cm/s. All tests were carried out in a sandy loam, at a moisture contents of 14% [45]. Similarly, tests were carried out with a high-speed direct shear device to determine the effects of sliding speed on soil friction. The range of sliding speed was between 0.3 m/s and 1.7 m/s, in four velocities [15].

Field Tests

Due to the large amount of space that is required for high velocity experiments, field tests are very common. To study the effects of the size, weight, and velocity of agricultural tractors on soil compaction, a two-wheel-drive Massey Ferguson model 285 tractor was tested at three forward velocity treatments of 0.78 m/s, 1.67 m/s and 2.5 m/s and the three levels of dynamic load on each rear tire of 7.27 kN, 10.30 kN and 13.50 kN. To examine the effect of tire dynamic load and forward velocity on cone index, bulk density, sinkage, and shear strength, a 3×3 randomized factorial design was used and replicated three times. Each plot was 50 m long by 4 m wide. For each tractor run, a straight course of 20 m was marked at 4 m intervals and cone index, bulk density, sinkage and shear strength were measured [46]. To study the effect of velocity on vehicle rolling resistance in sand, data was collected from single-wheel tests performed at the NASA Langley Landing Loads Track in Hampton, Virginia, shown in **Figure 20**. Tire velocity varied from 0 to 48.8 m/s. The ITTV is a 173.5-kN (19.5-ton) Ford CT 900 truck with pneumatic cylinders on the rear where a test tire can be mounted to avoid ruts [19].

Figure 20: *NASA ITTV with mounted test tire [19].*

To study the effects of tire inflation pressure and tractor velocity on dynamic wheel load and rear axle vibrations, an instrumented wheel, shown in **Figure 21**, was built to measure the wheel load, the longitudinal forces, and the lateral forces at a tractor rear tire. The instrumented wheel was tested with a tandem-axle trailer for manuevers over a ramp. The wheel load and lateral force can be measured at high tractor speeds of 18 and 27 km/h. The experiments were conducted on a dry smooth asphalt road of 50m long and on a sandy loam flat lane of 40 m long at different combinations of tire inflation pressure and tractor velocity [47].

Figure 21: *The tested tractor: (a) strain-gage-based transducers attached to the drive axle; (b) triaxial accelerometer under driver's seat [47].*

Controlled Soil Bin Tests

Indoor soil bins for testing tillage tools provide a practical means to carry out testing throughout the year, but the soil will never truly represent field conditions. The monorail system, shown in **Figure 22**, uses a 10-m long, 1.76-m wide, 0.4-m deep soil bin facility at the Department of Agricultural and Bioresource Engineering, University of Saskatchewan [17]. This monorail test system can reach speeds up to 10 m/s and was developed for studying the draught and power performance of narrow tillage tools operating at high speeds [16].

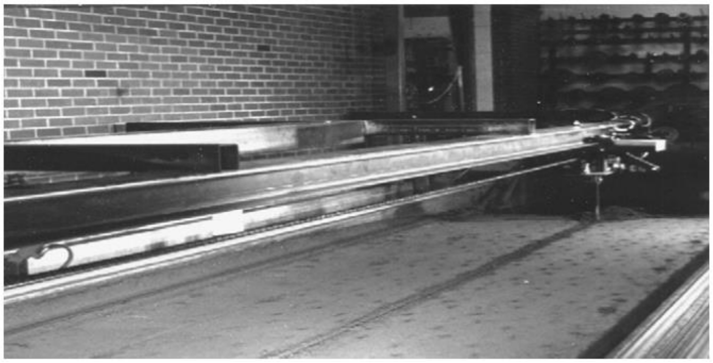

Figure 22: *Monorail system installed in a 10 m long soil bin [17].*

A long soil bin was built in 2010 in the Faculty of Agriculture, Urmia University, Iran, shown in **Figure 23**, to validate a high speed terramechanics model based on artificial neural networks and fuzzy data systems. This soil bin is 23 m long, 2 m wide, and 1 m deep. This long channel has the ability to hold a wheel carriage, a single-wheel tester, and different tillage tools. A three-phase electromotor of 30 horsepower was used to move a carriage through the length of soil bin by means of chain system along with the wheel-tester at speeds of about 20 km/h [14].

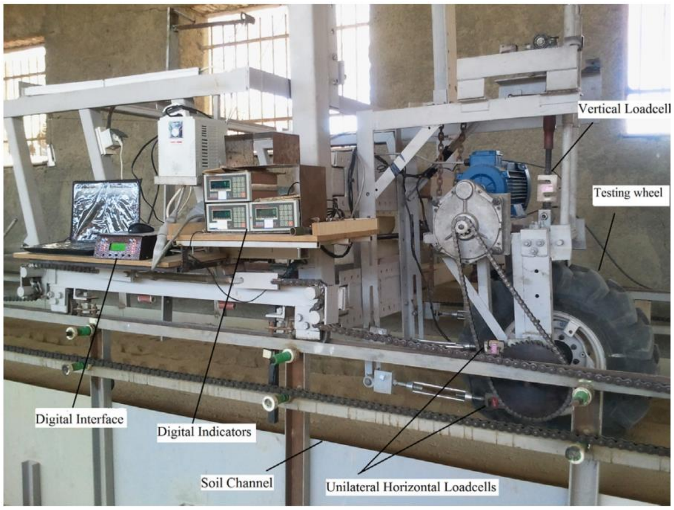

Figure 23: *System set up and components for laboratory tests [14].*

Scaling

Scale models have many advantages over full-scale machines for military applications. They include lower cost of construction, greater flexibility in the range of parameters that can be investigated, and closer control of test conditions. Models are best suited to basic studies of soil/machine relationships, and to comparative tests of configurations and operating conditions. Building experimental machine configurations is expensive. Too often, testing yields inconclusive or misleading results due to the non-homogeneity of the soil, and the non-uniformity of operator techniques [21]. Scale-model tests usually are conducted for one of two reasons : (i) To predict performance from values measured on a relatively small and inexpensive system, or (ii) To gain understanding of the nature, magnitude, and effect of the physical parameters that are present in the system whether defined or not [48].

Material Tests

Material tests in scaling analyses are commonly used to verify the scaling correlation and determine any correction factors for a particular soil-wheel interaction. For example, in an attempt to systematize the scale correlations for the various physical quantities involved in dynamic soil problems, several pressure-sinkage tests with varying plate sizes were used to verify the choice of scales used in the similarity experiments [22]. Scaling the soil material in these studies is difficult and involves the use of "artificial" soils. The term "artificial soil" normally refers to an admixture of soil solids--sand and clay--with a pore fluid other than water. The use of these fluids was intended to produce a time stable material with properties scaled in a proper relation to the properties of a naturally occurring soil. The actual use of physically compensated soil-machine models appears to have limited utility [49]. In fact, because it is so difficult to scale the independent variables characterizing the physical properties of soil to match the model and the prototype, it is common to use the same soil in both cases.

Field Tests

Due to the large amount of experiments that must be carried out to achieve same soil conditions, field tests offer limited utility to scaling analyses [48]. If the test area is large relative to the size and number of model tests to be conducted, then a single processing could suffice for all the tests. In this case, it is assumed that all portions have the same properties. If the field testing area is too small, it is required to run the experiment over the same set of soil. To achieve the same soil conditions, a rigidly prescribed sequence of manipulations is followed to return the soil to its original state. Considerable evidence, however, indicates that many soil conditions that should be the same because of repeated identical processing techniques are quite different and result in poor experimental repeatability.

Controlled Tests

To study the relationships between earthmoving machines and the soil, Caterpillar constructed a model laboratory at their proving ground in Peoria [21]. There are two main facilities a small soil bin, shown in Figure 24, and two parallel larger bins, shown in Figure 25. The small bin is 30 feet long, and contains a rectangular trough of soil 2 feet wide and 4 inches deep. It can accommodate scale models from 1/8 to 1/16 of normal size. A T-section monorail extends the entire length of the bin with a suspended carriage. A cable, driven by a hydraulic motor, propels the carriage along the monorail at actual speeds up to about 1.5 mph.

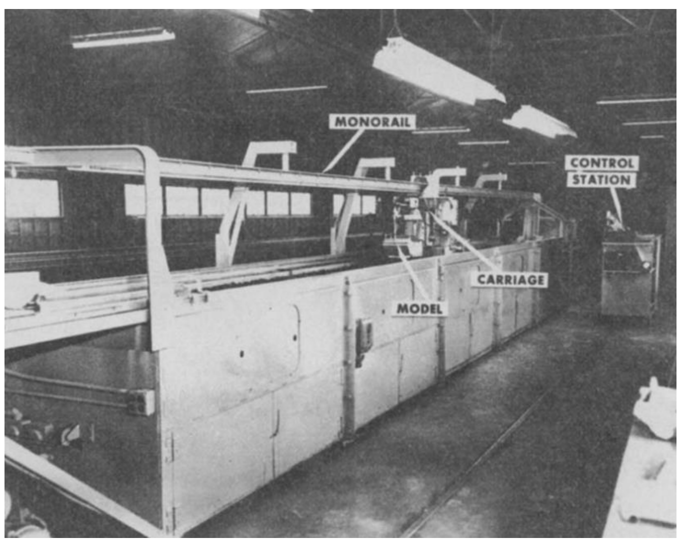

Figure 24: *Small soil bin [21].*

The large soil bins were built to perform correlation studies under controlled conditions. Models of from 1/3 to 1/6 of full size can be accommodated. There are two parallel bins, instead of a single bin, because it is relatively difficult to change soils in such large quantities. With two soils available, it should not be necessary to change very often. Each bin is 140 feet long, 4.5 feet wide, and 18 inches high. In the compacted state the soil is about a foot deep, so the total capacity of each bin is approximately 23 cubic yards. A 15 horsepower, 3 phase induction motor drives the variable-displacement pump of a hydrostatic drive. The variable-displacement hydrostatic motor drives both axles, through a gear box and roller chains. This arrangement provides smooth speed control up to a maximum of about 5 mph. Distances of a few feet at each end are sufficient for acceleration and deceleration [21].

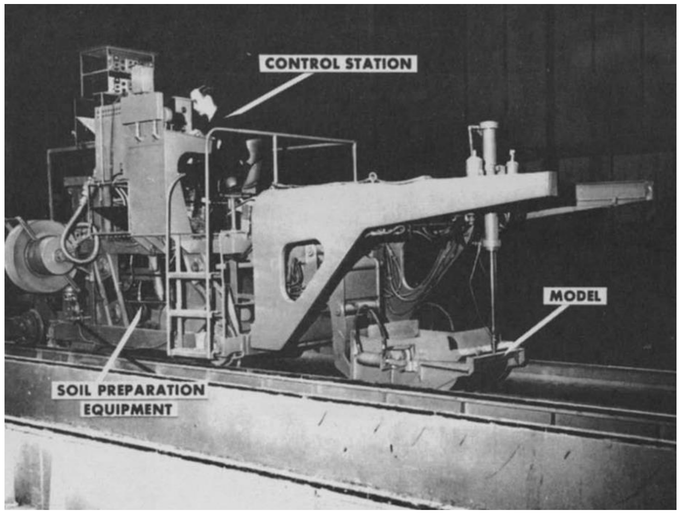

Figure 25: *Large soil bin [21].*

Scaling analyses have been used with some success to compare the performance of competing designs. To study the effectiveness of two earth anchors designed to enhance the resistance which the vehicle can derive from the ground during winching, scale models were created to verify performance predictions. The first design, shown in **Figure 26**, had a blade mounted on the front of the vehicle and was required to have a secondary bulldozing capability. The forces generated in the linkage system and in the hydraulic rams were measured using strain gauges to confirm theoretical predictions. In the case of the second design, shown in **Figure 27**, the blade was mounted on the rear of the vehicle for winching from the rear, and was not required to have a bulldozing capability. In this case, the reaction forces of the blade support arms on the hull were investigated using load cells. Although the results remain confidential, full scale trials on prototype vehicles have further confirmed these predictions and have thereby given support to the predictive capability of both theory and model scale investigations [23].

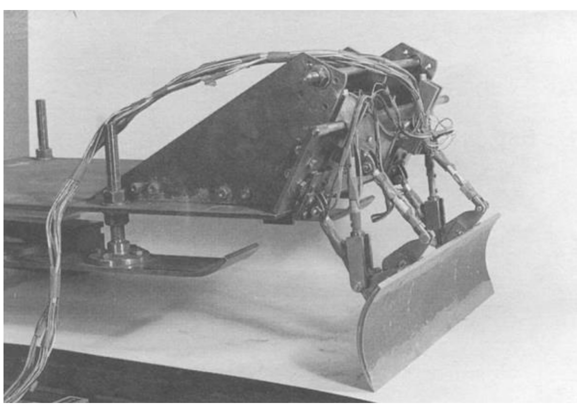

Figure 26: *1/8th scale model of Challenger ARRV [23].*

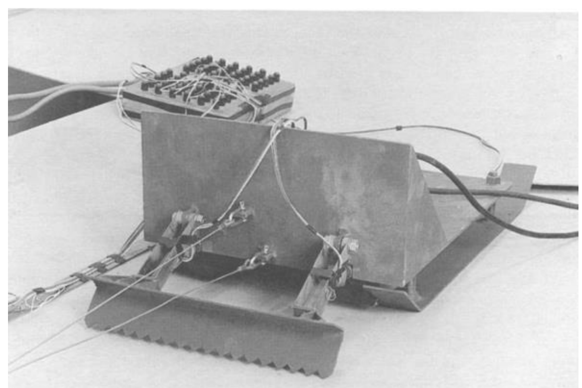

Figure 27: *1/8th scale model of Warrior recovery variant [23].*

To study the mobility performance of a battle tank and test the WES mobility numeric, a one-tenth scale, single-track model of a main battle tank was mounted within a carriage which runs on rails above a long sand bin (**Figure 28**). The carriage and the model, both electrically powered, are controlled and driven separately so that, by driving the model and carriage at different speeds, slip between the model and the ground can be introduced. The model is tethered to the carriage by an instrumented arm which measures the drawbar pull generated by the model. A full-size vehicle and a one-tenth scale model, of one thousandth the mass, have the same value mobility numeric [50], providing confirmation of the usefulness of the WES system of mobility numeric for predicting the performance of model tracked vehicles on sand.

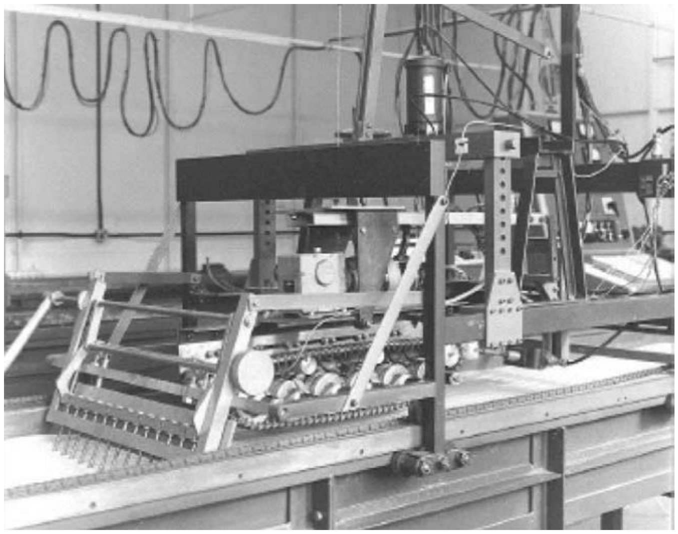

Figure 28: *Tracked model and carriage system [50].*

4 Recommendations

The following recommendations can be made based on the literature review:

- TARDEC once had a highly capable terramechanics testing facility. In order to be a leader in ground mobility, it is essential to have a state-of-the-art experimental facility.
- Despite a myriad of terramechanics facilities around the world, there remains a lack of understanding of key terramechanics phenomena, such as moisture effects, velocity effects, and scaling, due to the limitations in current experimental capabilities. Targeting these terramechanics phenomena will yield the most benefit to the scientific community.
- Despite the similarities of current terramechanics testing facilities, each laboratory has unique capabilities that could be useful for ground mobility tests.
- Controlled laboratory tests provide a practical means to carry out testing around the year, but the soil will never truly represent field conditions. It is necessary to supplement these laboratory tests with material and field testing.
- Military applications do not exist in a purely dry, sandy world. It is necessary to be able to predict the performance of a vehicle on moist soil.
- Velocity effects cannot be neglected, larger soil bins and field tests are required to perform these tests.
- Incorporating scaling at an early stage in the design process as a method of validating design proposals will provide significant financial savings and design improvements.

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