Experimental Analysis of the Effects of the Variation of Drawbar Pull Test Parameters for Exploration Vehicles on GRC-1 Lunar Soil Simulant

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ABSTRACT

A drawbar pull (*DP*) test procedure was developed at the NASA Glenn Research Center (GRC) for testing and developing designs for off-road vehicles. The motivation was to develop a procedure that would produce repeatable results and could be replicated by other researchers. While developing the test methodology, it became apparent that there was a certain degree of scatter in the results among identical tests. In order to characterize the disparities, an experimental study was conducted consisting of systematically varying specific test parameters. The selected performance metric was the *DP-TR* (travel reduction) relation. The selected parameters were: 1) the starting terrain condition, 2) the distance traveled by the vehicle under an applied, constant *DP* force, and 3) the density of the prepared terrain. Respectively, these parameters were selected to observe: 1) how differences in the starting area, or "launch pad," would affect the resulting performance of a test, 2) if a steady-state region of performance exists and how does performance change with the distance traveled, and 3) the relationship between prepared terrain density and performance. These experiments were conducted in a dry, granular, cohesionless, silica based soil called the GRC-1 Lunar Soil Simulant. The results of these studies were that the variations in both the starting terrain condition and the distance traveled did not significantly affect performance. The relationship between performance and terrain density was that only in a region of low density was the *TR* constant; subsequently, the *TR* decreased steadily with increasing density.

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Nomenclature

a	-	Vehicle acceleration (m/s^2)
CI	-	Cone Index (kPa)
DP	-	Drawbar Pull (N)
DP/W	-	Drawbar Pull Coefficient
DPR	-	Drawbar Pull Rig
D_R	-	Relative Density (%)
d_{ref}	-	Total distance traveled under specified reference condition (m)
F_T	-	Net tractive effort (N)
G	-	Cone Index Gradient (kPa/mm)
i	-	Cone penetrometer insertion number
m	-	Data point number for a given DP/W
n	-	Test number
N	-	Total number of repeat tests
n_{rev}	-	Total number of wheel revolutions
RB	-	Range bar at a given DP/W (%)
$r_n[m]$	-	Residual at a given DP/W (%)
r_R	-	Rolling radius (m)
r_h	-	Hard ground rolling radius
$s_n[m]$	-	Calculated TR from the test data for a given DP/W (%)
$s_n^{fit}[m]$	-	3rd order polynomial fit of TR value for a given DP/W (%)
T	-	Torque (N/m)

TR	-	Travel reduction (%)
v	-	Vehicle velocity (m/s)
v_{ref}	-	Vehicle velocity under a specified zero condition (m/s)
W	-	Vehicle Weight
x_i	-	Insertion depth (mm)
$\bar{x}$	-	Mean of x_i (mm)
y_i	-	Mean CI at a specific depth, x_i (kPa)
$\bar{y}$	-	Mean of y_i (kPa)
z	-	Sinkage (m)
α	-	Linearity Coefficient (kPa/mm^2)
θ	-	Total Wheel Rotations (rad)
ρ	-	Measured bulk density (kg/m^3)
ρ_{max}	-	Maximum bulk density (kg/m^3)
ρ_{min}	-	Minimum bulk density (kg/m^3)
σ	-	Standard deviation in TR (%)
ΣP	-	Resultant motion resistance force (N)
$\Phi[m]$	-	Standard deviation of TR for a given test (%)
ω	-	Wheel speed (rad/s)

1. Introduction

While developing vehicles and wheels for specific off-road applications, experimentally testing mobility in the laboratory is fundamental for comparing and assessing the capabilities and limitations of different designs. The primary methodology that has emerged for conducting such studies is called the drawbar pull (*DP*) test. The value of the *DP* test is that it describes how much work the vehicle can perform in addition to propelling itself through the terrain. However, many different test techniques and methodologies have been used, and the variety has made comparative and repeat studies difficult. In order to enable future collaborations and accelerate the development of off-road vehicles and wheels, more experimental information is needed so researchers can develop a test procedure that will allow their results to be compared and replicated. An important aspect of this development process, which is the primary objective of this thesis, is to understand how the variation of test parameters will affect the performance results.

An integral part of establishing such a procedure is to determine the sensitivity of the results to variations in test parameters. Understanding how test parameters will affect the results is important a few significant reasons: This introductory chapter describes the motivation for developing a standard test procedure at the NASA Glenn Research Center (GRC) and then outlines the content of this thesis.

1.1 Objectives

The main objectives of this thesis are: 1) to identify and publicize reasons for the need to establish a standardized *DP* test methodology to serve as a standard of comparison, 2) to develop a methodology to experimentally assess the effects the variations in *DP* test parameters on performance of a vehicle, and 3) to conduct and analyze these experimental studies to aid in the development of a *DP* test methodology at NASA GRC to be used as or incite a movement towards establishing a standard methodology.

The objectives of the variation of parameters studies are: 1) to identify sources of variability and avoid them or minimize the effects on the results, 2) create data processing and statistical techniques to account for variability that is inherent to the test techniques, and 3) to improve the economic efficiency of the experimentation without sacrificing the quality of the results.

1.2 Motivation

With the goal of creating or inciting a movement towards a establishing standard *DP* test methodology to be used for the development of off-road vehicles and wheels, a *DP* test methodology was developed at NASA GRC that was to be repeatable and easily replicated at other facilities. The importance for developing such procedure was realized by the difficulties that would be encountered in attempting to replicate previous studies used to predict the performance of lunar roving vehicles by the Army Waterways Experiment Station (W.E.S) in [1]. Even though the experiments in [1] were extensive and well documented, it is difficult to reproduce the results strictly because of differences in equipment, test techniques, and facilities.

Hence, similar situations in the future could be avoided if a specific test procedure was adopted as a standard for comparison.

If the facilities, equipment, and test techniques used in [1] could be exactly replicated, trying to reproduce the test results would still be difficult due to inherent variations of test parameters, such as slight differences in test techniques or preparation methods. As the wheel/soil interaction is already random in nature, any fluctuations in the test parameters can only add to the variability of the results. Therefore, an integral part of establishing a standard test methodology is to characterize the impact of variations in test parameters on performance. This information would allow for the inconsistencies among identical tests to be reasoned, and to differentiate between the performances of different vehicle and wheel designs, accounting for the expected variability of the test method.

1.3 Thesis Statement

I would like to indentify and characterize the effects of variations in test parameters on performance. Once the objectives are achieved, a more complete *DP* methodology can be developed to achieve standardization, which will facilitate comparative and replicate studies in the future. The general hypothesis is that variations in certain *DP* test parameters will cause variability in vehicle performance that is distinguishable, and is more significant than the random variability of performance due to the wheel/soil interaction. As the effects of the variation of test parameters will be significant, such a study must be conducted to identify which test parameters are influential, minimize their impact on performance, and otherwise characterize and account for them when analyzing performance results.

1.4 Main Research Contributions

The main research contributions of the author are stated subsequently:

1) Perform an analysis of previous studies to aid in the development of the test methodology at NASA GRC:
    a. Identify *DP* methodologies that have been developed, including testing and soil preparation, techniques, procedures, and metrics
    b. Analyze variation of test parameter studies that provide insightful information to aid in the identification of important parameters and to develop the methodology to conduct the studies in this thesis
2) Collaborated in the development of the *DP* test methodology at NASA GRC
3) Identified the importance of studying the effects of the variation of test parameters and formulated a working hypothesis
4) Development of the methodology experimentally analyze the effects of the variation of test parameters on the performance of a vehicle
5) Performed the experimentation and analysis of the aforementioned studies
6) Provided recommendations that were implemented into the NASA GRC methodology to avoid sources of variability associated with various test parameters, how to account for the variations in the analysis of the performance results, while improving the repeatability and increasing the economic efficiency *DP* testing.
7) Proposed generalized recommendations and provided insight regarding the value of conducting variation of test parameters studies for *DP* testing and how to develop the testing methodology, in addition to suggesting items for future work.

1.5 Thesis Outline

Chapter 2 includes background chapter provide to exemplify the knowledge obtained from a review previous studies and literature regarding methodology development for *DP* testing and variation of parameters studies. Also, relevant, standard definitions are provided, along with a theoretical derivation of the *DP* force, and an assessment of commonly used *DP* test techniques.

Chapter 3 consists of descriptions of the existing facilities and equipment at NASA GRC, in addition to the selected test vehicle and tires used for the variation of parameters studies. The second section derives the *DP* force and provides a discussion of its utility. The remained of this chapter discusses the selected soil used for the variation of parameters studies called GRC-1 lunar soil simulant and the terrain preparation procedures that were previously developed for the soil, which were investigated in this thesis.

Chapter 4 consists of an explanation of the developed *DP* testing methodology at NASA GRC. First, the testing conventions are described regarding the use and interpretation of previously used and standard conventions. Followed by the a description of the instrumentation and measurement techniques that were used for a typical *DP* test and for the variation of parameters studies. The chapter concludes with an explanation of a typical *DP* test at NASA GRC.

Chapter 5 describes the preliminary studies and investigation to develop the methodology of the variation of parameters studies. Note, these studies are not intended for interpretation, but for "lessons learned" and the contribution to developing the methodology. The first section describes the study on how performance varies among the T3, T2, and T1 terrain conditions. The next section describes the procedure developed to analyze the repeatability of a test technique, which is then applied to the 0.5 meter test technique. The third section describes a study to evaluate if a steady-state region of performance exists for a constant *DP* in a constant terrain condition. The final section describes a study on the effects of the terrain preparation density on performance.

Chapter 6 describes the revised variation of parameters studies that were conclusive. The first section discusses the application of an active *DP* control system. The second section is a reevaluation of the repeatability of the 0.5 meter test technique. The next section describes a study evaluating the effects of the starting terrain preparation on performance. The fourth section discusses the study regarding performance variability as a function of distance traveled at constant *DP*. The final section describes the effects of terrain preparation density on the performance. Each of these sections is subdivided into sub-sections describing the procedure, results, and recommendations for each study. The last section states the conclusions and recommendations derived from the variation of parameters studies.

Chapter 7 is the concluding chapter. The first section is a review of the *DP* test procedure and metrics. The section outlines the results from the variation of parameters studies and the recommendations for improving the test procedure and general recommendations. The final section presents suggestions for future work to continue to move toward developing a procedure to be used as a global standard for comparison.

2. Background

Researchers have been developing testing techniques to describe the performance of a single wheel or multi-wheeled vehicles on soft soils since the late 1950's. The test that has emerged to the forefront is the drawbar pull, *DP* test. The International Society for Terrain Vehicle Systems (ISTVS) defines drawbar pull as "the force available for external work in a direction parallel to the horizontal surface over which the vehicle is moving" [2]. While the drawbar pull test has been frequently unitized, no global testing procedure for has been established so far. In fact, the consistency of test results has varied significantly between researchers due to the employment of different testing techniques. Many past technical publications in this area have focused on performance relationships and modeling and lack significant investigation into testing techniques; few have primarily focused on evaluating the sensitivity of the results to testing conditions and techniques. Also, some important historical reports where variation of testing parameters has been investigated remain largely undistributed and infrequently cited in recent publications.

This chapter consists of background information that was used to aid the development of the *DP* test procedure at NASA GRC and conduct the variation of parameter studies. A literature review was conducted learn the definitions and utility of relevant test metrics, to understand and derive the *DP* force and its utility, to re-introduce valuable results from past drawbar-pull studies, and to identify important conclusions and shortcomings describing the sensitivity of the drawbar pull test results to testing techniques and conditions. Finally, an assessment is made comparing commonly employed *DP* test techniques and describes their utility.

2.1 Review of Literature

A review of literature was conducted to learn and understand the *DP* force and its utility, how the *DP* test has been used and how it has been evolved through time, and to identify variation of test parameters studies to aid in development of the hypothesis for the studies conducted in this thesis. This section consists of definition of relevant test metrics, theoretical derivation of the *DP* force, and an in-depth review of the development of the *DP* test through time.

2.1.1 Definitions of Relevant Test Metrics

This section provides definitions of common terminology and metrics involved with *DP* testing. These terms and metrics are universally used, but the symbolic representations, wordings, and implementations can differ between researchers based on the research goals and capabilities of their facility. The majority of the subsequent definitions used at GRC were extracted from or correspond with either ISTVS standards in [2] or ASAE standards in [3]. The specific definitions and metrics used at GRC will be discussed at the end of the chapter.

As a first step, in order to create a baseline for comparing in-soil performance, a zero condition must was established. The zero condition, as defined by the ASAE standards in [3], is the condition used to specify the rolling radius. Four possible zero conditions are: self propelled on a nondeforming surface, or on the test surface, or a towed condition on a nondeforming surface, or on the test surface [3].

The rolling radius, r_R, is defined by ASAE as the "distance advanced per revolution of the wheel divided by 2π under the specified zero condition" [3]. The rolling radius is calculated as:

$$r_R = \frac{d_{ref}}{2\pi n_{rev}} \tag{1}$$

r_R = rolling radius (m)

d_{ref} = total distance traveled under specified reference condition (m)

n_{rev} = total number of wheel revolutions

The rolling radius and the zero condition are used to calculate the travel reduction, *TR*, or slip, which are analogous. The travel reduction as defined by ISTVS, is "an indication of how the speed of the traction elements differs from the forward speed of the vehicle [2]. The travel reduction is a metric used to describe performance and is calculated as:

$$TR = \left(\frac{v_{ref} - v}{v_{ref}}\right)\times 100 = \left(1 - \frac{v}{v_{ref}}\right)\times 100 = \left(1 - \frac{v}{r_R \omega}\right)\times 100 \tag{2}$$

TR = travel reduction (%)

v = total distance traveled under operating conditions (m/s)

v_{ref} = total distance traveled under specified reference condition (m/s)

r_R = rolling radius (m)

ω = wheel speed (rad/s)

The drawbar pull force, *DP,* is defined by ISTVS as "the force available for external work in a direction parallel to the horizontal surface over which the vehicle is moving" [2] , and is a metric to describe performance. The *DP*, normalized by the weight of the vehicle, is otherwise known as the *DP* coefficient (*DP*/*W*). The *DP* is described in more detail and theoretically derived in Section 2.1.2.

The torque, or vehicle torque, *T,* is the "moment applied to the axle of the traction device" [3]. Typically an input, but can also be used to evaluate the increase in the output of a traction device if a constant wheel speed is the input.

The tractive effort, or net tractive effort, F_t, is "the total force output of the traction device acting parallel to the surface of the soil and in the direction of travel" [2]. The net tractive effort is the sum of the forces required to overcome all resistance forces and the available force to do additional work, or the drawbar pull force.

The power number, *PN,* was derived by W.E.S in [1] and is a measure of the energy consumed per unit distance of travel per unit of vehicle weight. The power number is typically represented as a number between 0 and 1, and can be calculated as:

$$PN = \frac{T\omega}{Wv} \tag{3}$$

PN = Power Number

T = torque (N/m)

ω = wheel speed (rad/s)

W = vehicle weight (N)

v = vehicle velocity (m/s)

The sinkage, *z,* of the wheel or vehicle is the distance from the bottom of the wheel to the level of the undisturbed soil [2].

The bulk density of a soil, or dry density, ρ, is the weight of the soil particles per unit of volume. The relative density of a soil is the ratio of the difference between the measured density and the minimum bulk density to the difference between the maximum and minimum bulk density [4], and is calculated as:

$$D_R = \frac{\rho - \rho_{\min}}{\rho_{\max} - \rho_{\min}} x100 \quad (4)$$

D_R = relative density (%)

ρ = measured bulk density (kg/m^3)

ρ_{max} = maximum bulk density (kg/m^3)

ρ_{min} = minimum bulk density (kg/m^3)

The cone index, *CI* was developed by W.E.S and is measured by the cone penetrometer. The cone index is an index of soil strength and is a measure of the penetration resistance of a right angle cone. The cone index gradient, *G* is the gradient of the cone index with cone insertion depth and is used to describe the density and consistency of the soil [5].

2.1.2 Theoretical Derivation of the Drawbar Pull Force

A drawbar pull test indicates the ability of a vehicle to do work in addition to propelling itself through a terrain. The International Society of Terrain Vehicle Systems (ISTVS) defines drawbar pull as "the force available for external work in a direction parallel to the horizontal surface over which the vehicle is moving" [2]. Hence, the *DP* is the net force that the vehicle can generate that is available for tasks such as slope climbing, towing, or plowing.

A schematic identifying the parameters of a 4x4 wheel drive vehicle during a drawbar pull test is shown in Figure 1. The forces acting on the vehicle, parallel to the direction of travel, are: the drawbar pull force, *DP,* resultant motion resistance force, ΣP, total vehicle thrust force, or tractive effort, produced by the vehicle, F_T, and the inertial force due to acceleration, *ma*. The other test parameters include the wheel speed, ω, wheel torque, *T*, vehicle weight, *W*, vehicle mass, *a,* vehicle acceleration, *a*, and vehicle velocity, *v*. A balance of these forces is in the direction parallel to the horizontal surface is written in Equation (5) [6].

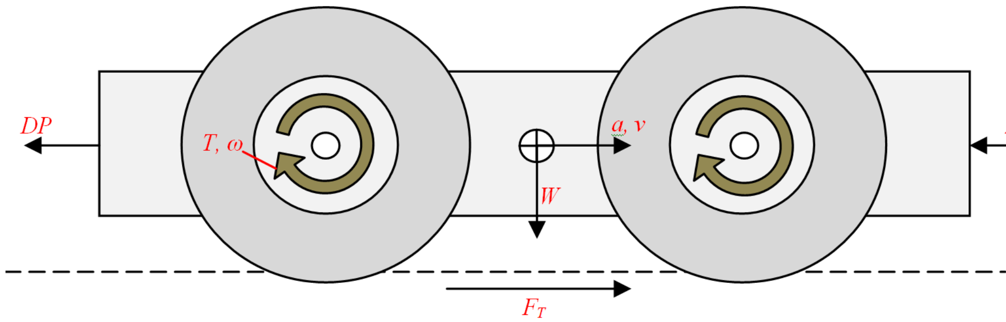

Figure 1. Schematic of a 4x4 wheel drive vehicle during a drawbar pull test [6].

$$m \cdot a + F_T = DP + \sum P \tag{5}$$

m = vehicle mass (kg)
a = vehicle acceleration (m/s)
F_T = tractive effort, net (N)
DP = drawbar pull force (N)
$\sum P$ = resultant resistance force (N)

If the velocity is held constant, the inertial force is zero. Setting the inertial force to zero and rearranging Equation (5) gives Equation (6) [6].

$$DP = F_T - \sum P \tag{6}$$

Equation (6) illustrates the aforementioned definition of the *DP* force. *DP* is the difference between the total tractive effort produced by the vehicle and the total resultant motion resistance forces, and quantifies the net force available for the vehicle to perform work in addition to propelling itself.

2.1.3 Development of the Drawbar Pull Test

The U. S. Army Engineer Waterways Experiment Station (W.E.S) began performing drawbar pull tests in the 1960's. The goals were to investigate how wheel parameters would affect the performance of the wheel in dry sand, results that could be immediately applied to tire selection for Army vehicles [5]. The applicability of drawbar pull testing results was still novel at that time, and, in order to hastily produce results, the engineers made critical assumptions to expedite testing. By the early 1970's, the engineers were able to more completely understand the consistency and the sensitivity of the results to variations in test parameters and techniques. However, the trend to this day for all researchers has been to develop in-house procedures and make assumptions that are largely specific to their facility or the experiment at hand.

In 1969, Green and Murphy published in [7] that the pull-slip relations for single-wheel tests conducted in air-dry sands conducted at W.E.S did not agree closely with the pull-slip relations reported by others, particularly those obtained from multi-wheel vehicle tests. Specifically, for similar tires operated in sand, W.E.S test results indicated that maximum pull occurred at 20% slip, where other investigators observed continuous increase in pull with slip, a significant inconsistency. Hence, the uniqueness of the pull-slip relationship and the validity of using single-wheel tests to predict vehicle performance were questioned. "The postulation that tire-soil relations may depend on testing technique employed was preferred" [7].

Before investigating testing techniques, the definition of performance metrics must be checked for consistency amongst researchers, where performance metrics are used to describe the ability of a wheel or vehicle to move through a terrain. The drawbar pull performance metrics which W.E.S used were first defined in [5] and are similarly defined today.

A valuable technique of communicating drawbar pull performance results is to compare the ability of a wheel or vehicle to move through a terrain relative to a reference condition. For drawbar pull studies, this reference condition is known as the zero condition. ASAE defines the zero condition as the "condition is used to specify the rolling radius," and the rolling radius as the "distance advanced per revolution of the wheel divided by 2π under the specific zero condition" [3]. Therefore, the distance traveled per revolution in soil can be compared to the distance traveled per revolution on to depict the relative performance on the soil to the zero condition. A popular method to establish the zero condition, which has been used by the National Soil Dynamics Lab, is to use hard artificial surfaces, such as cement, at zero net traction, as the zero condition [8]. Using a hard surface is advantageous because "it provides uniform and reproducible test conditions which enable valid comparisons to be made between [wheels and vehicles] tested at different times and in different countries" [9]. Also, comparing performance relative to a hard surface is useful because of the familiarity with driving a vehicle on a road. Thus, using hard ground to establish the zero condition is easily repeated and is consistent, and should not be a source of inconsistency in performance results.

Once defined, the zero condition is used to calculate the travel ratio. The travel ratio is "the ratio of the distance advanced per revolution of the traction device under operating conditions, to distance advanced per revolution under the specified zero condition" [3]. The aforementioned definition of travel ratio can be normalized by time to obtain another applicable definition of travel ratio of actual velocity to the velocity at the zero condition. Therefore, either vehicle velocity or distance traveled can be measured to calculate the travel ratio. The slip or travel reduction of a wheel is "one minus the travel ratio" [3]. Slip and travel reduction, where travel reduction is the preferred term, are used to describe the performance. Travel reduction can be subjected to inconsistency between researchers if a repeatable zero condition was not established as a means of comparison.

Dimensionless metrics have been defined to make comparing results more efficient. An important and frequently used metric is the pull coefficient, which is the drawbar pull force normalized by vehicle weight. By normalizing the pull force by vehicle weight, the performance of any variety of vehicles can be compared because the metric of comparison is the pull force as a fraction of vehicle weight. The torque number is derived in the same manner, where the torque at the axle is normalized by diameter and vehicle weight [10].

The next step in identifying reasons for inconsistency in the drawbar pull results is to examine the terrain itself and how the condition of the terrain can be prepared and evaluated consistently. The measurement device that has been used as a standard for comparison is the cone penetrometer. The cone penetrometer was developed by the Waterways Experiment Station for use in drawbar pull studies. The original design of the field instrument consisted of a right-circular cone, mounted on the end of a rod which is mounted on a proving ring and a dial gage. The cone is inserted into the soil at a constant rate, the force is measured by the dial gage, and the depth is measured by markings on the shaft. The applicable metric is the cone index, *CI* which is defined as force per area [5]. Dean Freitag defines the cone index as an "index of soil consistency of strength," "where the magnitude of the cone index at any depth in the soil is determined by the soil properties." Because the dry soil is cohesionless, the magnitude of the cone index with depth must be due to the confining pressure. Therefore, the cone index is the first approximation of the specific weight, or relative density of a soil, which is the ratio of the difference between the actual density and the minimum density compared to the difference between the maximum and minimum density. Green, Smith, and Murphy observed that the internal friction is dependent on the specific weight [11]. Freitag later concluded that the cone index is related to the internal friction and the confining pressure. With further analysis, Freitag concluded that the average rate of increase of the cone index with depth, or cone index gradient, is a measure of the specific weight of the sand [12]. Oravec, Zeng, and Asnani later employed this relationship to design and perform trafficability tests on lunar soil simulant. By utilizing cone penetrometer gradient measurements taken from astronauts during the Apollo missions, a lunar soil simulant was created by adjusting relative density to match the lunar soil measurements. The internal friction angle of the soil simulant was found using triaxle tests [4] . From the data obtained from such tests, it can be inferred that the relationship between each of these soil parameters is deterministic and that the soil condition can be characterized by the cone penetrometer gradient. Therefore, on multiple accounts, the applicability of the cone penetrometer method to drawbar pull tests becomes apparent because it has been shown to be an adequate measure of soil consistency and its properties.

The cone penetrometer is, in general, easy to use and is considered a satisfactory measure of the soil consistency, but the applicability of the cone penetrometer gradient to predict vehicle performance has been scrutinized. By 1972, it had been shown that the energy transferred to the soil was dissipated in two forms: "deformation energy losses relating to subsoil distortion and volume change, and interfacial energy losses due to slip effects and high soil distortion at the contacting surface" [13-15]. Hence, research was needed to determine if these soil/wheel interactions could be correlated to the measurements taken by the cone penetrometer.

In 1993 Godbole, Alcock, and Hettiaratchi [16] claimed that the soil/wheel interactions could not be characterized by the cone penetrometer because, "the cone penetrometer fails to take surface effects into consideration and bears little or no analogy with the mode of operation of the traction tyre" [16]. In 2009, Way and Wulfsohn [17] supported the claim in [16] by stating that "extensive testing over a range of soil conditions has indicated that cone index is not a reliable parameter to use in classifying soil properties relevant to traction… …both because it is not a good indicator of horizontal soil strength and because of the inherent variability of measurements, especially when using hand-driven devices" [17]. These conclusions were made utilizing the W.E.S experiments along with a large body of previous work dating back to the 1960's, and brought into question the applicability of the cone index method to characterize vehicle mobility.

In the mid 1960's, when drawbar pull testing was still novel, W.E.S began investigating the feasibility of using the cone penetrometer gradient to predict performance. In 1965 Freitag [12] developed the sand mobility number, which is a dimensionless metric based on the cone penetrometer gradient, wheel and vehicle parameters. A relationship was found between the sand mobility number and the performance metric of drawbar pull force which could be used to predict vehicle performance [12]. Wang later determined in [18] that using only the sand mobility number to predict vehicle performance was not sufficient. However, W.E.S would continue to investigate the applicability of the cone penetrometer to predict performance in future studies.

In 1967, Green [19] conducted experimental testing on a four-wheeled vehicle. The tests were performed outside of the laboratory in conditions that did not follow a linear soil strength-depth relationship. Therefore, it was necessary to evaluate how these deviations would affect the vehicle performance; hence, it became important to quantify how large deviations of cone penetrometer gradient would affect the vehicle performance. To do so, tests were conducted in prepared soil which exhibited abrupt changes in soil strength at various depths. The results from these tests were that changes in soil strength below a depth of approximately 0.83 times the width of the tire did not significantly affect the level of performance [19].

Further investigation was conducted in 1970 by Freitag, Green, and Melzer [1]. They were interested in understanding the effect of soil strength on performance, and characterizing how variability in soil conditions would not only affect the vehicle performance in the field, but also how inconsistencies in the soil preparation could affect the test results. Relative density was chosen as the metric to define the soil conditions because it provides a qualitative means of comparing performance in different soil conditions. A series of tests was performed to evaluate the pull to weight ratio when the load and soil condition were changed, holding all other variables constant. The relative density of the soil was varied from approximately 30% to about 90%. The lighter loads did not exhibit significant performance variation with changing soil conditions, whereas the heavier loads resulted in large variations in performance as the soil condition changed. The general trend identified between the soil condition and the pull to weight ratio was as follows: the pull to weight ratio increased with relative density and the rate of increase of the pull to weight ratio decreased with relative density. Therefore, it can be concluded from here that large fluctuations in the prepared soil condition could result in significant variation in performance if the fluctuations are severe [1].

Due to the aforementioned trend, further analysis was necessary to determine if performance could be modeled utilizing the relationship between the relative density and the angle of internal friction. The angle of internal friction is the amount that the shear strength of as soil increases with pressure [12]. The authors performed an extensive soil analysis to define the standard soil properties required to characterize the soil, such as the friction angles and densities. This analysis is tedious and time consuming, and the comparison between the soil potential, as calculated from the friction angles of the soil, and actual performance through experimental analysis had not yet been thoroughly researched up to 1970. The result of this comparison was that the soil potential does not help explain the trends in the stress and deformation characteristics of the soil. Hence, the relation between friction angle and performance could only be established experimentally [1]. While this inhibited the possibility of using the cone penetrometer gradient as a mean of predicting vehicle performance, it does not suggest that there is no correlation between them either.

A more general approach was taken by Freitag, Green, Melzer, and Costes in 1972 [20] to develop the correlation between cone penetrometer measurements and vehicle performance. They used the cone penetrometer to measure the relative density of the sand. Further testing indicated "pull and pull to weight ratio increase with relative density, but their rate of increase decreases with increasing relative density" [20]. This type of conclusion illustrates of the extent of using the cone penetrometer for contemporary research. While not particularly useful for predicting performance, the cone penetrometer gradient can provide an indication of the compaction of the soil used to gain an understanding of general trends between performance and soil condition. For example, in 2009, Taylor [21] defined ranges of cone penetrometer gradient values to describe soil conditions for which performance was assumed to be repeatable [21]. The cone penetrometer is simple, cheap, easy to use, and is able to be employed in understanding vehicle performance; however, other methods of predicting the vehicle performance have been researched, as well.

The US Army Corps of Engineers developed a numerical approach to predict vehicle performance in 1995 [22]. Based on the data from many previous experiments, such as those performed by the W.E.S, a numerical algorithm was created that relates the sand mobility number to performance metrics such as in-soil rolling resistance, drawbar pull, required input torque, and wheel sinkage. The sand number is derived from the cone penetrometer index, wheel width and diameter, and vehicle weight. The sand number is then carried through a series of equations to predict performance [22]. This method is dependent on a large volume of experimental data, and would not be readily applicable for new technologies where sufficient experimental performance data has not been collected, e.g., for new rover wheel designs.

An alternative approach, not reliant on cone penetrometer measurements, was proposed by Wittig in 1990 [23]. The objective was to use a Single Wheel Tester to determine soil strength from performance metrics. This study was conducted by applying multiple loads to the wheel, and measuring the maximum developed torque. The slope of the plot of normal load versus maximum torque was used as the soil potential term [23]. This method employs an experimental approach to obtain a metric to predict the performance of a wheel on the testing soil. While applicable to laboratory tests, single wheel testing cannot be readily performed in the field, where, on the other hand, cone penetrometer measurements can be taken easily.

As illustrated in the aforementioned discussion, the use of the cone penetrometer to predict performance has been thoroughly scrutinized and has generally been accepted to characterized soil condition and strength using the cone penetrometer gradient metric. However, previous studies have indicated that the cone penetrometer gradient is not a sufficient metric to predict vehicle performance, but is generally applicable to determine trends in performance that are dependent on soil strength.

Once a consistent soil condition has been established and measured using the cone penetrometer, the next step is to determine if the vehicle performance could be dependent on the testing technique. The first characteristic of a drawbar pull test that must be analyzed is the starting condition. Understanding the starting condition is important because abrupt accelerations could affect the steady state response. In 1969, Murphy and Green [7] hypothesized that an abrupt start, for a single wheel test, would result in large inertial forces and greater than normal sinkages which would cause the wheel to not achieve the same steady state performance compared to a test where these conditions are minimized. This hypothesis was tested by creating three initial conditions: starting on a steel plate where the desired slip is established before entering the soil, starting directly on the soil, and starting embed in the soil approximately 10-11 inches. The initial conditions in and on the soil reached the desired slip within the 2-3 feet of travel. The results contradicted the hypothesis. The conclusion of this study was that when the wheel reached a specified slip, the pull, torque, and sinkage were all independent of the starting conditions. The only disadvantage of a quick start is the large traction force needed to accelerate the mass of the vehicle [7].

Understanding how the type of drawbar pull test can affect the prediction of the vehicle performance is important because different researchers have used different methods based on their resources, facilities, time, and cost constraints. For example, when considering the large size of the testing matrix for his dissertation in 1965 [12], Freitag understood the importance of time efficiency. In order to cut out some experiments, he chose to investigate if a programmed-slip test would provide the same performance versus the steady-state, constant-slip or constant-pull tests. A programmed-slip test was conducted by increasing slip at a constant rate, and a constant-slip test was conducted where the wheel and vehicle speed were held constant for the entire length of the test bin. With all conditions held constant, four test methods were used to find interrelationships: controlled-slip, controlled-pull, programmed-slip, and towed tests. The constant-slip/pull tests were defined as traveling a distance of 20 feet, and the programmed-slip test is defined as uniformly ramping up the forward velocity of the machine while the wheel speed is held constant. Freitag generated pull-slip curves in both sand and clay for each testing method. The number of data points collected for the controlled tests were statistically significant to define a pull-slip curve as compared to the programmed tests. The conclusion was that "within the precision of the data, the same pull-slip relation is obtained from the programmed-slip tests as from the steady-state tests." Hence, the pull-slip relationship could be generated for the entire curve with this testing method of uniformly ramping up slip throughout the test [12]. Using this method, it is unclear as to whether the pull-slip relationship at a specific slip value would be consistent from test to test. Also, because Freitag performed only single wheel tests, the reliability of this method cannot be extended to 4x4 vehicle testing. Nevertheless, he was able to make assumptions and justify his decision for using a programmed-slip test.

Considering Freitag's decision, Murphy and Green [7] identified that the different drawbar pull test techniques could be a source of variability in performance results for single wheel tests. To evaluate the effect of the techniques used to obtain the test results, a test matrix was created where both slip and pull were controlled. First, programmed-increasing and programmed-decreasing slip techniques were compared. During a programmed slip test the slip of the wheel is controlled to increase/decrease uniformly with distance. The programmed-decreasing slip tests consistently produce greater pull and torque up to at least 15 percent slip. Next, the pull-slip relationship was obtained and compared for both the constant-slip/pull and programmed-slip/pull techniques. Constant-slip/pull tests are defined as the wheel traveling 20 ft at constant slip or pull. The scatter amongst the results of the different techniques was compact and the techniques were difficult to differentiate. Therefore, the authors concluded that for increasing slip/pull, testing technique had no effect on the performance of the wheel for a single wheel test. Comparing decreasing and increasing slip/pull tests is subject to variability in performance [7].

2.2 Assessment of Drawbar Pull Test Techniques

Drawbar pull tests can be conducted in a variety of ways, but as discovered in Section 2.1.3, there are a few commonly used techniques that have been chosen based on the research goals and the capabilities of the testing facility. When designing the testing facility and equipment, engineers must first evaluate the tradeoff between testing single-wheels and testing multi-wheel vehicles. Each may be advantageous, depending on how the results will be used, and those goals must be defined when choosing between these techniques. Next, a procedural level decision is to determine which test variables will be controlled. Most commonly, either the *DP* force or the travel reduction, *TR* of the vehicle, a.k.a. slip, are controlled and all other variables are measured during the test. These tests are termed controlled-pull or controlled-*TR* tests in this report. This section will describe the tradeoffs between these techniques and their utility, and served as a basis for the development of the *DP* test procedure at NASA GRC described in Chapter 4.

2.2.1 Single-Wheel Tests vs Multi-Wheeled Vehicle Tests

Single-wheel tests and multi-wheeled vehicle tests have both been used historically, and both techniques have their advantages and disadvantages. The choice of which technique to use should reflect the goals of the research. Single-wheel tests have been used to model and compare wheels and also to model the wheel-terrain interaction. The advantage of conducting a single-wheel test, as opposed to a vehicle test, is the lack of vehicle dynamics influencing performance. Hence, one would expect better repeatability by having more control over the test, where the results would be well suited for modeling. For instance, the Army Waterways Experiment Station (W.E.S) has employed single-wheel tests to evaluate the performance of soils under tire loads in the late 1960's. The single-wheel tester used by W.E.S in Vicksburg, Mississippi is shown in Figure 2. The single-wheel test allowed for dimensionless metrics to be derived relating soil and wheel parameters to performance metrics [12]. Also specific relationships were formed between performance and parameters such as inflation pressure, wheel diameter and width, deflection, sinkage, cone index [10, 19, 24].

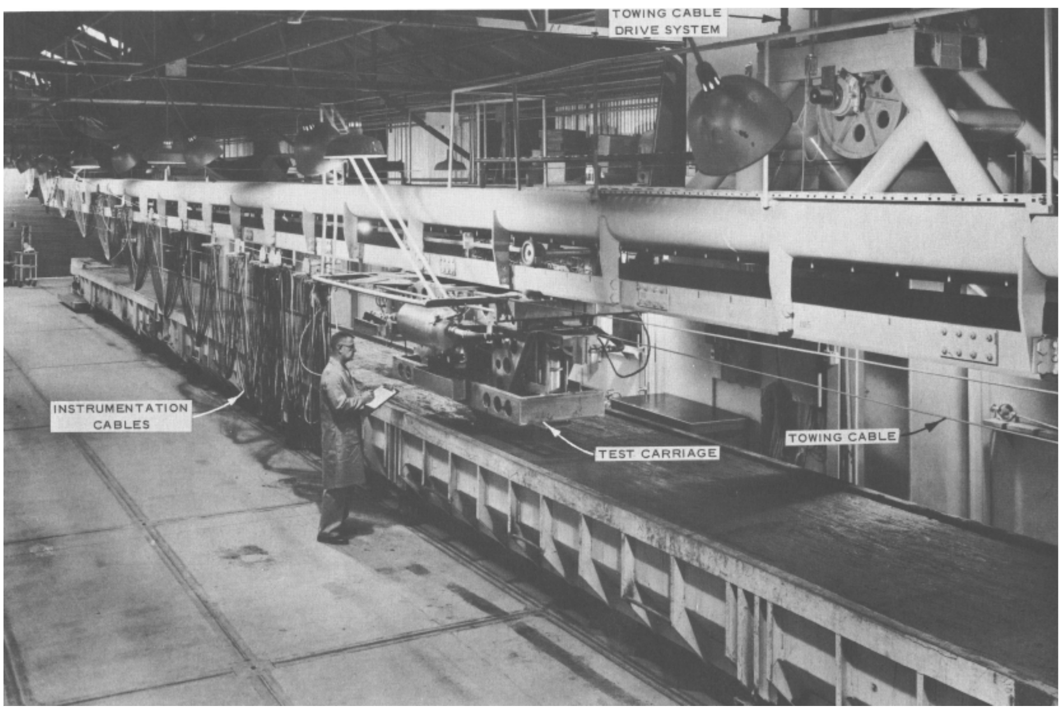

Figure 2. The single-wheel tester used by the Army Waterways Experiment Station (W.E.S) in Vicksburg, Mississippi [5].

A contemporary example is the single-wheel tester developed at the Advanced Vehicle Dynamics Lab of Virginia Tech and is shown in Figure 3. This tester was utilized for collaborative studies between Virginia Tech and NASA GRC to develop *DP* test and terrain preparation methodologies. One of these studies was conducted by Taylor in [21] to test and model how individual wheel parameters (wheel diameter, width, and compliance) would affect the performance of rigid and flexible wheels on dry sand. These specific studies, as well as others, have shown that the control over and repeatability of a single-wheel test is very useful for comparing wheels and modeling wheel-terrain interactions.

Figure 3. The single-wheel tester developed in the Advanced Vehicle Dynamics Lab (AVDL) at Virginia Tech in Blacksburg, VA [21].

While single-wheel tests provide valuable information for modeling and comparing wheels, there are factors that affect a vehicle's performance that cannot be simulated by single-wheel tests. Specifically, a single-wheel test cannot emulate the dynamics experienced by a full vehicle while subjected to external loads and traveling through a terrain. In [19], Green investigated if multiple passes of a single-wheel could be represent the performance of a multi-wheeled vehicle. He found that the single-wheel results indicated consistently higher *DP* for the same conditions as compared to the vehicle tests. Green proposed possible causes for the contrasting data could be due to "differential wheel slip (front to rear and/or side to side), uneven wheel loading due to dynamic load transfer, and increased rolling resistance caused by imperfectly tracking rear wheels." Hence, single-wheel tests are not a reliable predictor of multi-wheel vehicle performance.

Multi-wheeled vehicle tests are used for simulating the actual performance of a vehicle or wheel set while under external loads and traveling through a terrain, but require significantly more space to conduct as a full vehicle is used. But, because a single-wheel test is not reliable for predicting full vehicle performance, testing of the full vehicle is advantageous if possible. Vehicle testing is especially important for understanding how an exploration vehicle will perform in its simulated environment. By including the dynamics as stated by Green [19], a more reliable characterization of performance can be developed because the actual vehicle is being tested and observed. For example, in [1], W.E.S conducted 4x4 wheel drive vehicle test to evaluate how lunar wheels would perform on the Moon. These full vehicle tests were performed because understanding how vehicle dynamics would affect the performance of the wheels would help avoid overestimating the performance, as multiple passes of a single-wheel test would indicate [19], which could eventually jeopardizing the lunar mission. Although performing full vehicle tests are important for the aforementioned reasons, an adverse effect of incorporating vehicle dynamics in performance will complicate any modeling tasks. The transient dynamics associated with vehicle tests will generally lead to decreased repeatability because the dynamics itself is difficult to replicate. Thus, one may conclude that multi-wheeled vehicle tests are important when vehicle dynamics are necessary to completely understand vehicle performance, but are generally not as useful as single-wheel tests for modeling performance.

2.2.2 Controlled-*DP* vs Controlled-Travel Reduction (Controlled-*TR*)

The relationship between the *DP* force and the travel reduction, *TR*, or slip, is commonly used to characterize the performance of a vehicle or wheel. In order to obtain this relationship, one of these variables is controlled, the independent variable, and the other is the measured, the dependent variable. The selection of which technique to use is a procedural level decision and the tradeoffs are discussed subsequently.

Both techniques have been used historically to generate relationships between *TR* and *DP*, and the results using either technique have generally been considered consistent, but are plotted differently as the independent variable is different. In terms of the techniques themselves, the difference is that for controlled-*DP* tests, the *DP* force is controlled, and for controlled-*TR* tests, the speed of either the vehicle or wheel is controlled. Although the results from using either technique might be indistinguishable, controlling the different variables, and the method of control, will inherently produce different dynamics. The choice to employ either technique must be made considering the goals of the research. While other variables such as sinking, torque, and the power number can be measured for each of these techniques, this discussion will focus only on the effect of the technique type on the relationships between *TR* and *DP*.

During a controlled-*TR* test, specific *TR* values are obtained by controlling either the translational velocity or wheel speed while holding the other constant. The independent variable is *TR* and the dependent variable is the *DP*, producing a *DP*-*TR* relation. A sample plot is shown in Figure 4. Each data point in Figure 4 is found by forcing the desired *TR* magnitude and measuring the *DP* produced by the wheel or vehicle. The control over *TR* was obtained using different methods by W.E.S in [1] and by Taylor in [21] . W.E.S controlled *TR* by holding the wheel speed constant and varying the translational velocity, where Taylor chose to use the contrary. While both methods produce consistent results, the technique used by W.E.S is more representative of the dynamics of a vehicle because the inertia of the test apparatus is being adjusted accordingly.

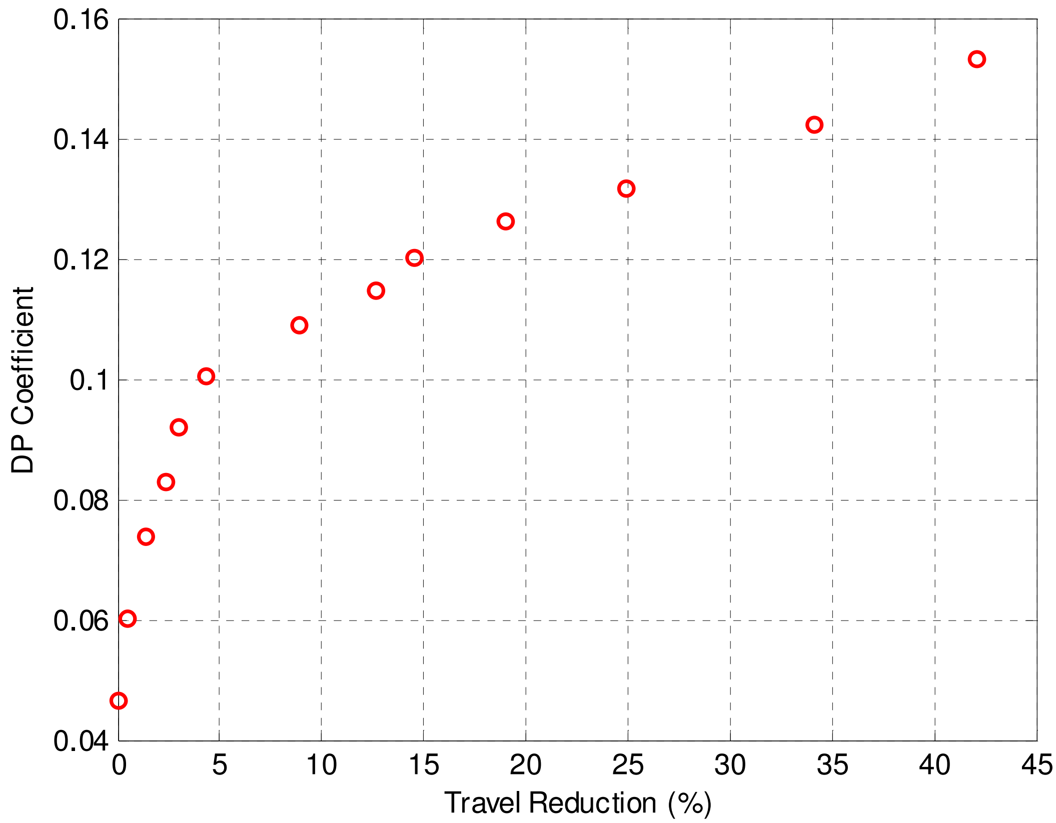

Figure 4. A sample *DP*-*TR* relation obtained using the controlled-*TR* test technique.

During controlled-*DP* test, the wheel or the vehicle is subjected to a *DP* force and the *TR* of the vehicle is measured. A sample *TR*-*DP* relation from a controlled-*DP* test is shown as Figure 5, where *DP* is the independent variable and *TR* is the dependent variable. Here, the desired *DP* force is applied to the test apparatus or vehicle while the wheel speed is held constant. The resultant *TR* can then be calculated for each magnitude of *DP*. This technique is the representative of the tractor pull, which is used as a standard measure of tractor performance in the agricultural industry.

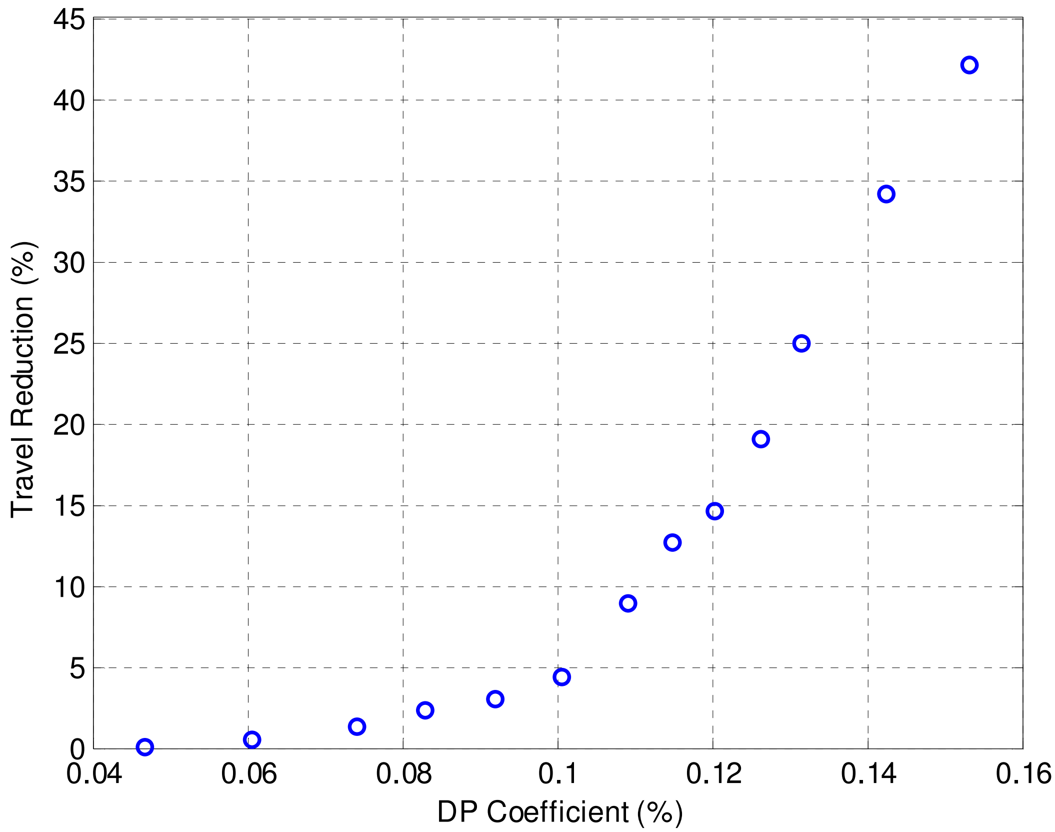

Figure 5. A sample *TR*-*DP* relation obtained using the controlled-*DP* test technique.

Murphy and Green conducted a study on a single-tester in [7] to determine if the controlled-*DP* test would produce the same results as a controlled-*TR* test. While they found the *DP*-*TR* relations to be similar, subjecting a wheel to large *DP* forces resulted in variations of carriage velocity and a stable condition for a constant *DP* force was difficult to obtain. Whereas, for a controlled-*TR* test, a stable condition for *DP* is achieved for a constant magnitude of *TR*.

Therefore, for single-wheel tests, Murphy and Green concluded that a controlled-*TR* test was better suited for defining *DP*-*TR* relations.

For vehicle tests, controlling *TR* requires a high frequency feedback system to control and adjust the wheel speed to keep a constant *TR*. This is cumbersome and vehicle tests are more easily performed using a controlled-*DP* technique. However, when controlling *DP*, small changes in high magnitudes of *DP* can result in large fluctuations in *TR*, which can be deduced from Figure 5 where the *TR*-*DP* relation becomes steep at high levels of *DP*. One may conclude that, controlled-*DP* vehicle tests will more accurately represent the performance of the vehicle, but controlled-*TR* vehicle tests, while more difficult to conduct, would be less sensitive to variations of the independent variable

2.3 Summary

Drawbar pull testing is a valuable tool to characterize wheel and vehicle performance on sand. However, no experimental procedure or testing technique is currently adopted to serve as a standard for comparison, and even though the same metrics have been employed, data collected by different research groups has been difficult to compare. Inconsistencies among performance results have been attributed to both the utilization of different test techniques and to the randomness of the soil and the wheel/soil interaction, but the affects are not well understood and are largely uncharacterized. It is evident, that in order to allow for collaborative research in the future, short of adopting a procedure acting as a standard for comparison, the sensitivity of performance results to variations in techniques and test parameters must be investigated to create a body of knowledge to help explain inconsistencies in results.

3. Facilities, Equipment, and Soil used in the Study

This chapter contains descriptions of the Simulate Lunar Operations Facility (SLOPE) at the NASA Glenn Research Center (GRC) in Cleveland, Ohio, and the equipment and soil selected for the variation of parameters study. Following the explanations of the SLOPE Facility, the drawbar pull rig (DPR), test vehicle, and test tires are described. Lastly, the GRC-1 lunar soil simulant was the selected soil and is described with the existing terrain preparation and verification procedures that were investigated in this study.

3.1 Existing Test Facility at NASA GRC

All of the vehicle drawbar pull tests were conducted in the Simulated Lunar Operations (SLOPE) Facility at the NASA (GRC). The SLOPE Facility is shown in Figure 6. The SLOPE Facility contains a large soil bin consisting of 12 m x 6 m x 0.3 m flat region and a 6 m x 5 m x 0.3 m adjustable tilting region. The tilting region can be adjusted up to a 45 degree slope used for slope climbing experiments. The flat region is divided into two equal areas, one side originally contained golf course sand, as pictured in Figure 6, but currently is under renovation to increase the soil depth for deep sinkage testing. The other side and the tilted region contain the GRC-1 lunar soil simulant which is described in Section 3.5. Testing was conducted only in the GRC-1 soil in the flat region of the soil bin.

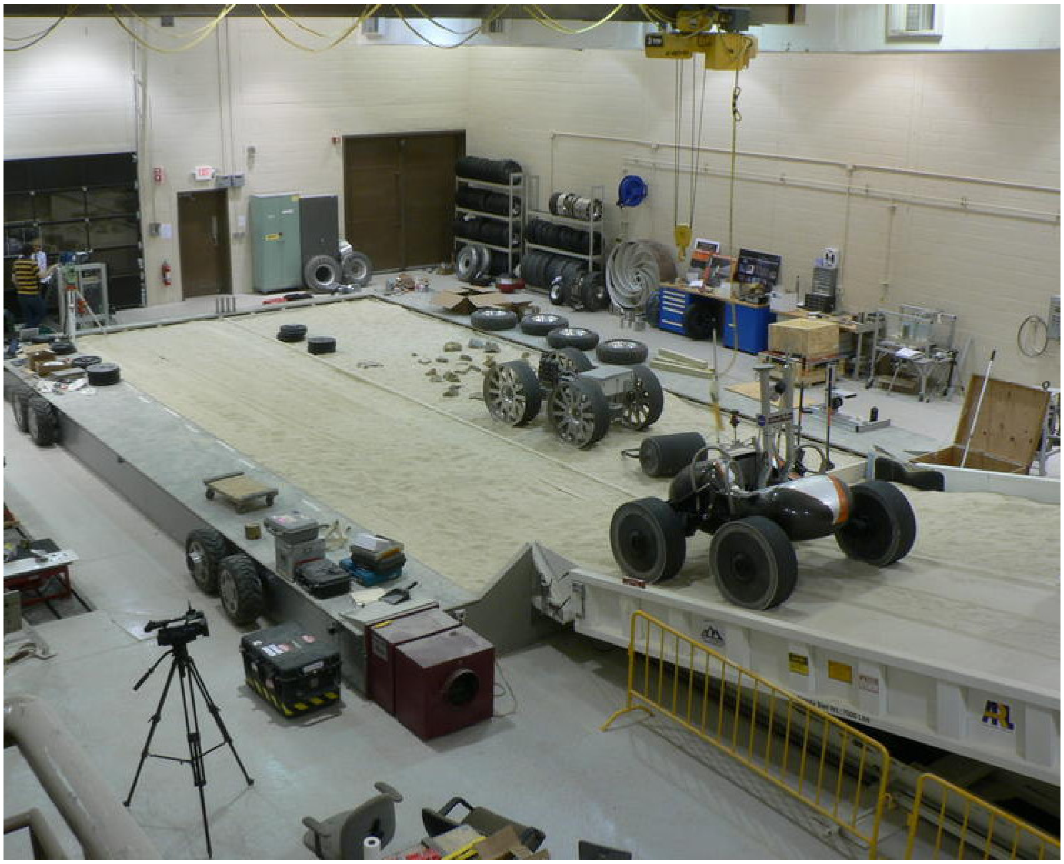

Figure 6. The Simulated Lunar Operations (SLOPE) Facility at NASA Glenn Research Center [6].

3.2 Description of the Existing Drawbar Pull Rig (DPR) Used in the Study for Controlled-*DP* Tests

A drawbar pull rig (DPR) was developed at NASA GRC to conduct controlled-*DP* tests, which are described in Section 2.2.2. The DPR was selected for use in the variation of test parameters studies because the controlled-*DP* test will better simulate actual vehicle operations as compared to controlled-*TR* tests. The DPR applies an external *DP* force to the test vehicle by retracting a steel cable that is attached to the vehicle. The drawbar pull rig is shown in Figure 7.

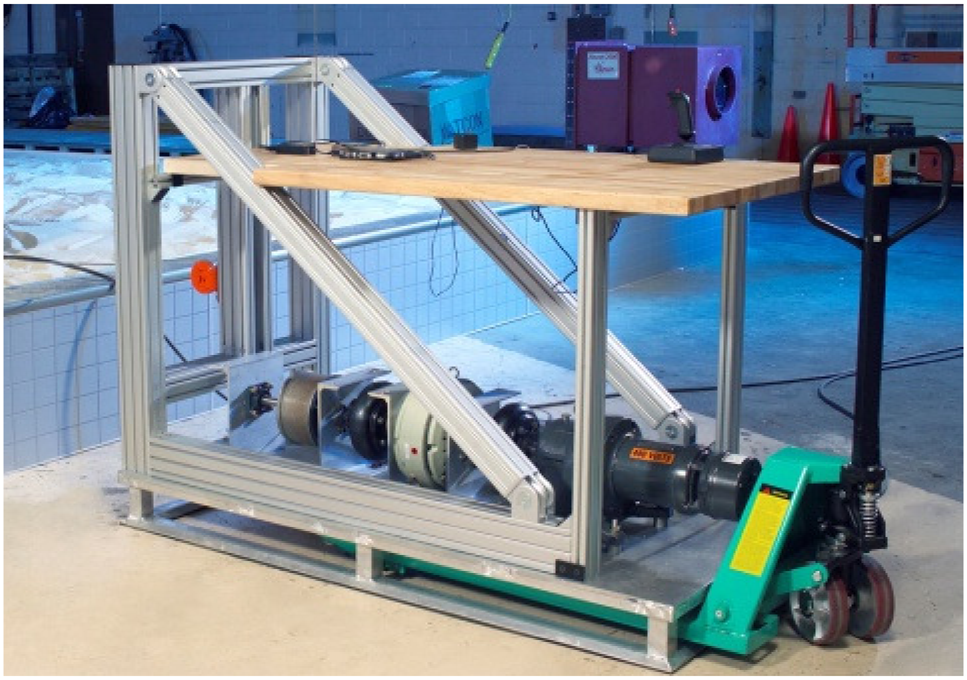

Figure 7. The drawbar pull rig used to apply a drawbar pull force to the test vehicle via a cable [6].

The DPR is designed to hold a constant tensile force while the cable is release, retracted, or stationary. This is accomplished by retracting the cable by winding it around a cable drum that is attached to a motor via a magnetic particle clutch. The drum is identified in Figure 8. The torque in the drum creates the tension in the cable that acts as the *DP*. The magnitude of the torque in the drum is controlled by adjusting the current that the magnetic particle clutch receives while the motor is running with a current source. A *DP* up to 1780 N can be created by the rig. A block and tackle configuration can be implemented to apply more force.

A rotational encoder in the drum measures the number of drum revolutions which is proportional to the length of cable that is drawn out. This data is used to calculate the distance the vehicle has traveled. These measurements are transmitted to a computer via USB. The encoder is calibrated while the cable is under tension to account for the stretch and slack of the cable.

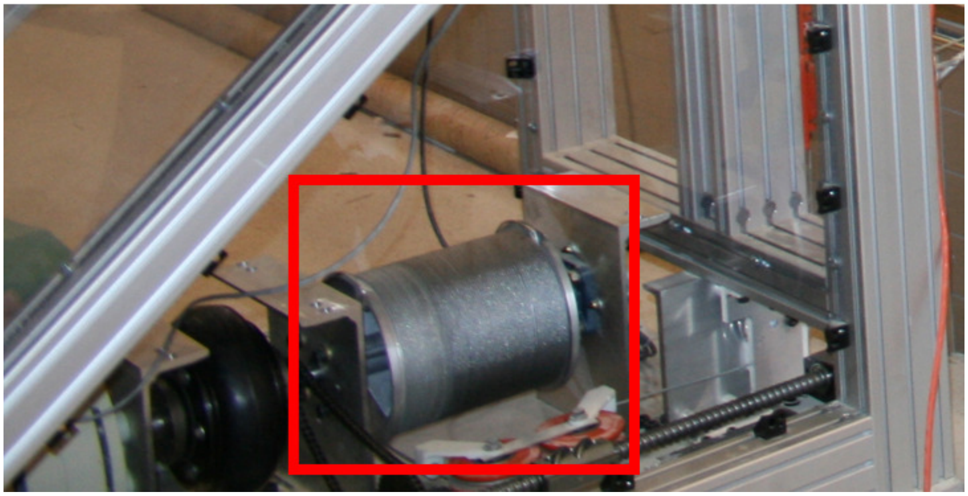

Figure 8. The cable drum on which the cable is wound in the drawbar pull rig. A rotational encoder in the drum measures drum revolutions, which is later converted to vehicle distance traveled [6].

The cable is connected to the vehicle by a cable pulley and hook. The cable travels from the DPR, around the pulley, and is reattached to a fixed point on the DPR. The pulley is connected by its hook to a load cell, which is used to measure the *DP* force. The load cell is connected by a hook to the vehicle hitch, which is attached to the rear wheel hubs of the vehicle. This configuration was used for the *DP* experimentation in this report and is shown in Figure 9.

The hitch was selected to be attached to Scarab at the rear wheel hubs. Hanamoto found in [25] for tracked vehicles that the hitch height where the *DP* force is applied has significant effects on performance as the height varies. This variation in performance was caused by the *DP* forcing the vehicle to pitch. The pitching motion caused the weight distribution to change and resulted in larger sinkage in the rear of the vehicle. He recommended that the hitch height be located near the "traction-producing level." Considering this study, when the hitch location for Scarab was selected, any vehicle pitch due to the application of the *DP* force was noted. By ensuring the cable height from the DPR matched the hitch height, only a horizontal force was applied, and no significant pitch was observable, except at extremely large *DP*. Because vehicle pitch was negligible, and these heights were kept constant for all tests conducted for this report, the assumption was made that the same pitch would occur for each test and no differences in performance would result.

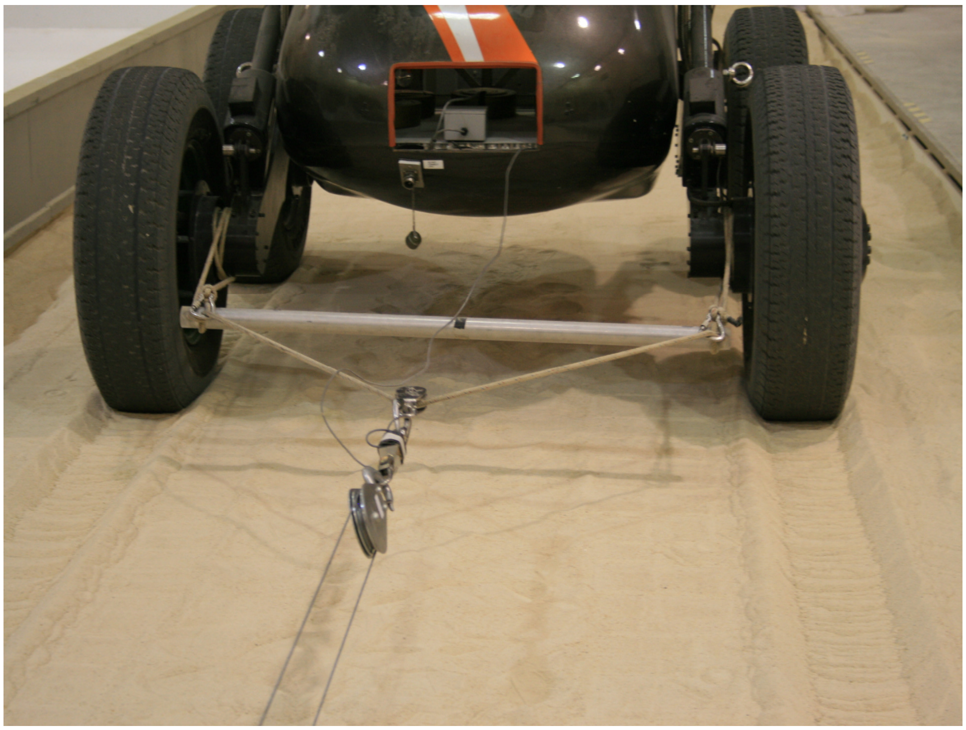

Figure 9. The drawbar pull force is applied by a cable connected to a load cell and the hitch attached to the wheel hubs on the rear of the vehicle.

3.3 Selected Test Vehicle for the Variation of Parameters Studies

The test vehicle used for all drawbar pull tests in this thesis is named Scarab and was designed by the Robotics Institute at Carnegie Mellon University (CMU) as a robotic Lunar Vehicle. Scarab is shown in Figure 10. It was designed to drive autonomously on the Moon while collecting and analyzing samples from the ground. As described by its developers in [26], Scarab has a low center of gravity for stability, uses skid steering as opposed to explicit steering, and employs an active adjustable kinematic suspension. In the lab, Scarab is wirelessly controlled by the user via an external computer communicating with an onboard, Scarab computer. A web browser based software acts as the user interface.

Figure 10. Scarab in a leaning position on the tilted soil bin in the SLOPE Facility [26].

Scarab is a 4x4 wheel drive vehicle that is used to simulate high wheel loads of lunar vehicles ranging from 981 N (100 kg) to 2475 N (250 kg) per wheel. As described in [26], "each of the four wheels are independently driven. A brushless motor, planetary gearhead, and harmonic drive are embedded at the hub." The unloaded vehicle weight without wheels is 2740 N (280 kg) [26]. Additional load is achieved by inserting free weights either into the body of Scarab or into the wheel hubs. Weight is applied to the wheel hubs by attaching steel posts using bolts that are screwed into threaded holes in the wheel hub. Scarab is shown in Figure 11 at the 2475 N (250 kg) wheel load with the said free weights applied to the wheel hubs.

Figure 11. Scarab during a drawbar pull test with a wheel load of 2475 N (250 kg) [6].

Scarab is used as a test vehicle at the GRC because the design of the vehicle enables multiple types of driving modes to be studied. The wheel speed and direction can be independently controlled for each wheel. (Adjusting the wheel speeds to steer the vehicle is called skid steering.) The wheel hubs are connected to a unique, actuated shoulder joint that allows the wheel base to be adjusted independently on each side of the vehicle, allowing Scarab to lean. This ability is shown in Figure 10 as Scarab is positioned on the tilted soil bin at the GRC. Scarab can also drive in an "inch worm" mode. By adjusting either the front or rear wheels while keeping the opposite in place, and alternating this process, Scarab can extend and contract to crawl though the terrain.

While Scarab is versatile, it was selected for the variation of test parameters studies because it could be driven autonomously, the wheel speed could be controlled for each wheel, and the measurement capabilities of the vehicle. The driving mode used for the drawbar pull testing in the thesis was inputting a hard ground vehicle speed of 0.035 m/s, which corresponds to a wheel speed of 0.1 rad/s for all of the wheels. This driving mode is particularly useful because the wheel speed can be reliably controlled for each wheel and the vehicle will drive in a straight line. The wheel base for straight line driving for drawbar pull tests was set as 1.2 m and the wheel load was always set to be identical for each wheel.

The Scarab data acquisition system was used to measure the drawbar pull force, wheel rotations, and wheel motor current. These measurements are obtained by a load cell, wheel rotational encoders, and a current meter located in the wheel hub, respectively. Once the system is initiated, all of these measurements are taken and recorded with a time stamp. The data is obtained by wirelessly accessing the onboard hardrive and downloading the files to an external computer.

3.4 Selected Test Tires for the Variation of Parameters Studies

A variety of tires were available for testing at NASA GRC, but the specific tires that were used in the studies in this thesis were the Scarab rigid tire, Spring Tire, and a treadless pneumatic tire, and they are described below.

The Scarab Rigid Tire is shown in Figure 12. The diameter of the tire is 71.2 cm and the width is 22.9 cm. The rigid wheels at GRC are used for high wheel loads and as a baseline wheel to eliminate the dynamics exhibited by flexible wheels.

The Spring Tire is shown in Figure 13. The average diameter of the tire is 74.1 cm and the average width is 18.3 cm. The Spring Tire was fabricated from springs and can deform to navigate obstacles. It was designed for exploration vehicles and to operate under high tire loads.

The treadless pneumatic tire is pictured in Figure 14. It is a Goodyear bias-ply tire with official sizing of ST225/75R15. The tread was shaved off of the tire to be used for comparative testing between a pneumatic tire and tires designed for exploration vehicles. The inflation pressure can be varied to match the deflection under load of other exploration tires.

Figure 12. The 71.2 cm x 22.9 cm Scarab Rigid Wheel [6].

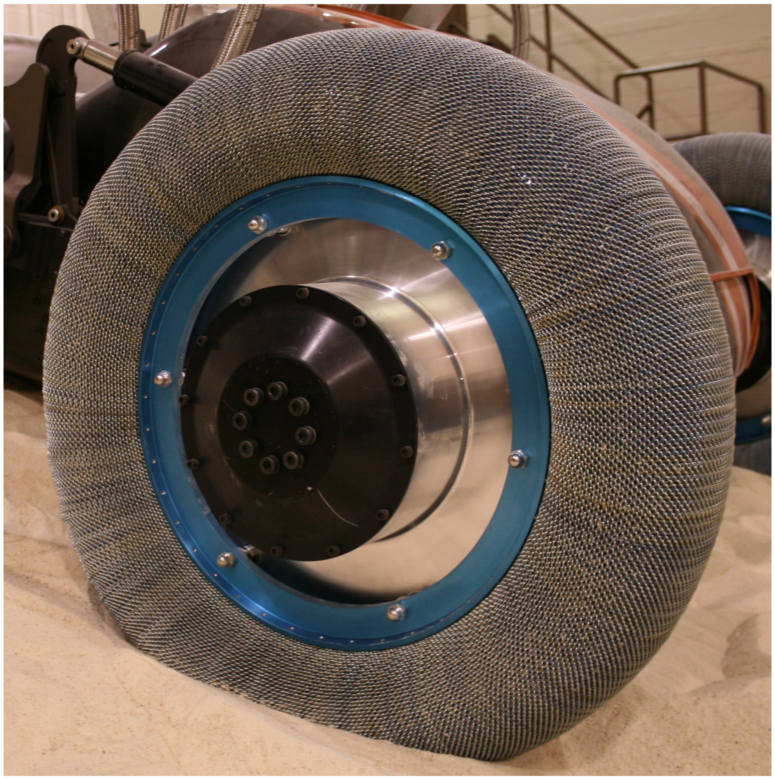

Figure 13. The 74.1 cm x 18.3 cm Spring Tire [6].

Figure 14. The Goodyear ST225/75R15 treadless pneumatic tire.

3.5 Description of the Soil and Terrain Preparation used in the Study

While many soils are available for testing at NASA GRC, the selected soil used for the variation of parameters studies in this thesis was the Glenn Research Center-1 (GRC-1) lunar soil simulant. The GRC-1 soil was developed in [4] to replicate the properties of the lunar terrain. As this soil is new and unique, it was a prime candidate for studying how performance would change with variations of test and soil parameters. Also, conducting such a study in this soil was immediately applicable for future studies at GRC, but the results could possibly be generalized for other dry, granular, and cohesionless, sandy soils. In addition, a complete soil analysis was available in [4] and repeatable terrain conditions had been developed to achieve various densities. This section includes a description of GRC-1 and the terrain preparation and verification procedures that were used and investigated in this thesis.

3.5.1 Existing Glenn Research Center-1 (GRC-1) Lunar Soil Simulant

Again, the selected soil used for testing in this thesis was the Glenn Research Center-1 (GRC-1) lunar soil simulant is the soil on which all *DP* test discussed in this thesis were conducted. Oravec, Zeng, and Asnani [4] developed the soil simulant to conduct tractive performance testing of lunar vehicles on a surface that has similar properties and deforms like the lunar soil. GRC-1 was created by mixing readily available manufactured sands to replicate the properties of the lunar terrain. The density of the mixture was then varied to replicate cone penetrometer gradient measurements taken by the astronauts on the Apollo 15 and 16 missions. The cone penetrometer gradient measurements from various regions on the Moon taken by the Apollo astronauts are shown in Figure 15. The dots shown in Figure 15 are cone penetrometer measurements taken at specific relative densities of the simulant and a line of best fit is drawn through them. GRC-1 does not properly replicate the lunar terrain at high densities, but is representative of the lunar soil in the looser conditions where the majority of lunar terrain measurements were taken [4].

To conduct testing in GRC-1, three different terrain conditions were developed and defined based on their preparation method, and are called the T3, T2, and T1 terrain conditions. The definition of these terrain conditions using relative soil properties are shown in Table 1 and illustrated in Figure 15. The three terrain conditions are able to simulate the lunar terrain conditions where the majority of the measurements were taken, and are repeatable within the standard deviations and linearity coefficients specified. The linearity coefficient along with the statistical method for verification of the terrain conditions are explained in Section 3.5.2.4. The following section describes the preparation methods for each terrain condition.

Table 1. GRC-1 terrain conditions and the corresponding metrics used for evaluating and describing the soil preparation [6].

Metric	T3 Terrain Condition	T2 Terrain Condition	T1 Terrain Condition
Mean Cone Index Gradient, *G* (kPa/mm)	2.5 ± 0.5	3.5 ± 0.5	5.0 ± 0.3
Mean Standard Deviation, σ (kPa/mm)	< 0.5	< 0.5	< 1.0
Linearity Coefficient, α (kPa/mm^2)	0 ± 0.01	0 ± 0.01	0 ± 0.015
Mean Relative Density, D_R (%)	11	23	41
Mean Bulk Density, ρ (g/cc)	1.63	1.66	1.71

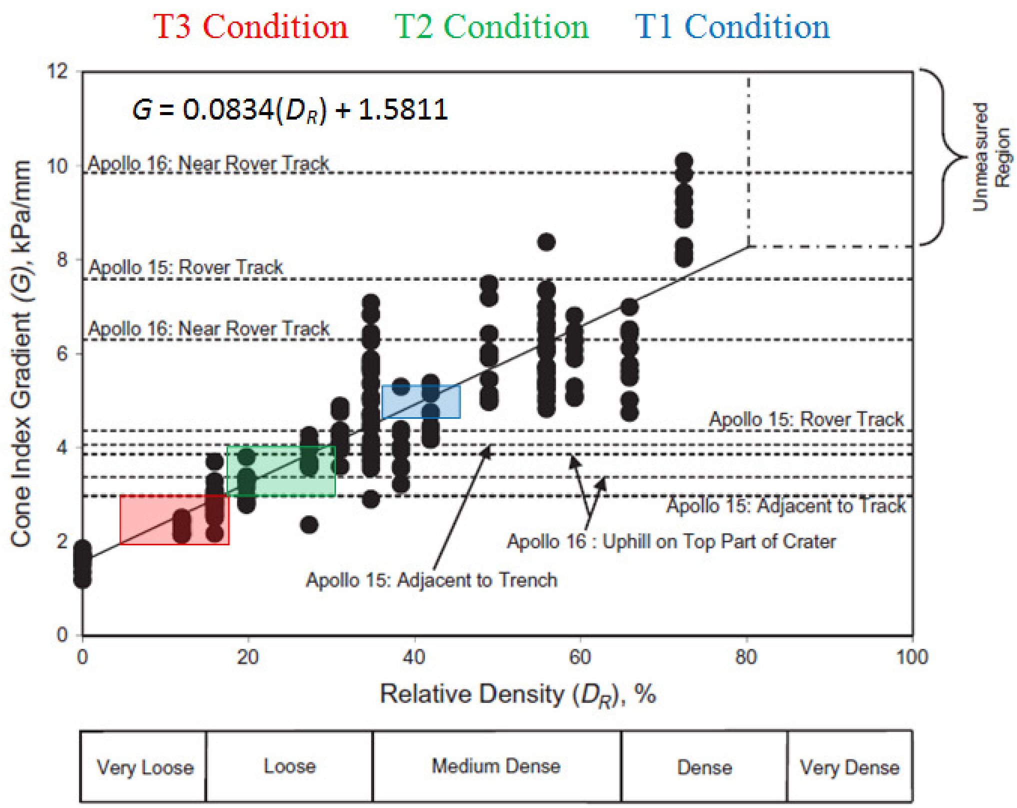

Figure 15. The GRC-1 terrain condition types overlaid on a plot showing the relationship between the cone index gradient, *G* and relative density, D_R [4].

3.5.2 Existing GRC-1 Terrain Preparation and Verification Procedures Investigated in this Study

This section provides a description of the terrain preparation and verification procedures that were used and investigated in this study.

3.5.2.1 T3 - Terrain Condition Preparation

The T3 terrain condition is the loosest of the terrain conditions at a density of 1.63 g/cc. The related parameters defining the T3 condition is located in Table 1. In terms of the preparation of all three terrain conditions, the T3 condition is prepared first; to obtain the T2 and T1 conditions, additional compaction is necessary.

The preparation starts with loosening the soil to eliminate any artifacts from previous disturbances. This is accomplished by using a flat shovel and inserting it into the soil so that the shovel is vertical. After pushing the shovel down to the bottom of the soil bin, the user then gently pulls the handle back approximately 45 degrees to lift and loosen the soil. This inserting of the shovel is shown in Figure 16. The shovel is then gently pushed forward back to its vertical

Figure 16. The first step to prepare the terrain is to use a flat shovel, insert it vertically into the soil, and gently pull backwards 45 degrees to loosen the soil.

position and then removed up and out of the soil. This action will produce a mound in front of the shovel where the soil was lifted and pushed forward and a depression behind the shovel. The next insertion of the shovel should be located just behind the depression created by the previous stroke. This loosening process is conducted for both sides of the vehicle, three passes for each side, to create a test lane for the vehicle to travel in. One pass is shoveling from in front of the wheel to the end of the bin. The first pass is centered in front of each tire, second and third passes on the left and right of the first pass. Each of the side passes overlap the center passes by approximately one-third of width of the shovel. The passes of the loosening pattern, the mound and depression created by the shoveling, and the fully loosened test bin is shown in Figure 17.

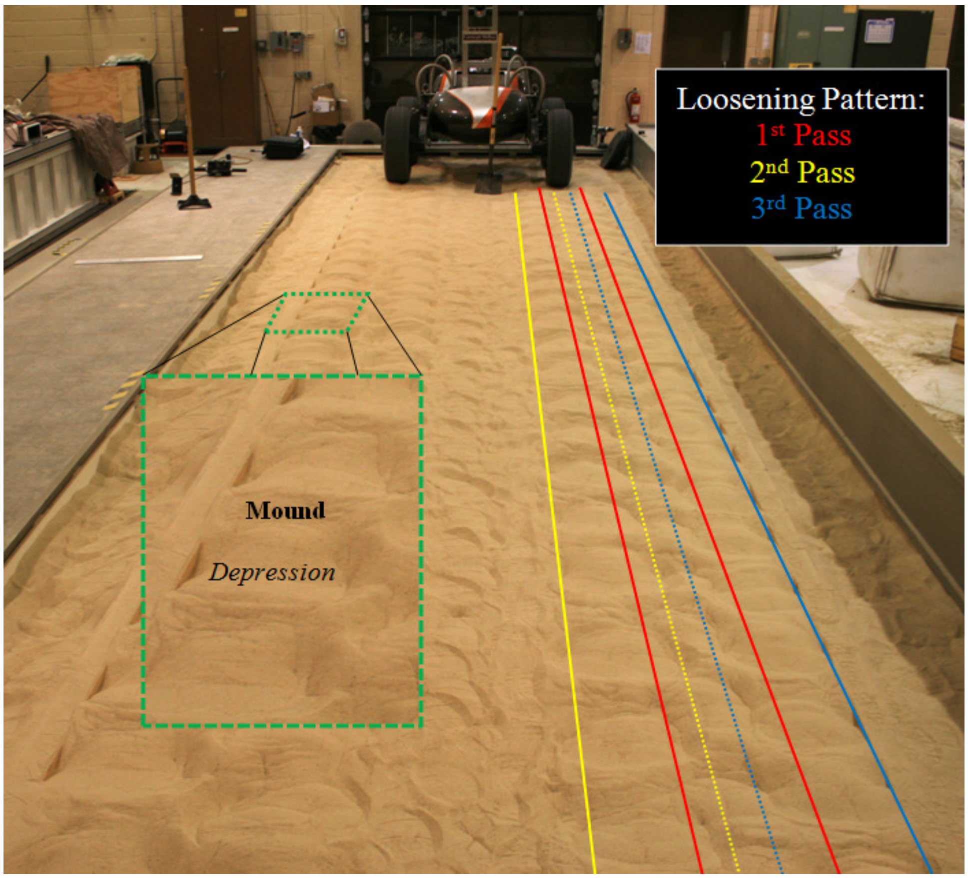

Figure 17. The loosening process of the soil preparation consists of three passes, and the shoveling process creates a mound and depression.

The next step of the terrain preparation is to rake the soil using a landscape or bow rake, which is shown in Figure 18. Starting at the end of the test lane and moving toward the vehicle, the rake is pulled at a constant rate and at a slight angle off parallel to the test lane. This technique will evenly distribute the soil in the test lane and sufficiently remove the mounds and depressions caused by the loosening process. Any voids left after raking are filled using a shovel and lightly pouring the soil to fill the holes.

Figure 18. Raking the soil is necessary to evenly distribute the soil in the test lane and to remove the mounds and depressions from the loosening process.

The final step in preparing the T3 condition is to level the soil to create a smooth and flat test lane. A leveling blade is pulled across the soil by the user starting at the vehicle and moving toward the end of the prepared soil, and is pictured in Figure 19. The ends of the leveling blade are pulled across two by fours built into the soil bin. This allows the soil to be leveled consistently and also to not cause the blade to compact the soil. This leveling process is repeated until the soil is evenly leveled.

Figure 19. The soil is leveled using a leveling blade to create a smooth and flat surface.

3.5.2.2 T2 - Terrain Condition Preparation

The T2 condition is denser than the T3 condition, at 1.66 g/cc, and is defined in Table 1. The T2 condition follows the same steps as described in 0 for the T3 condition, but requires one additional step. This additional step is the compaction of the soil to increase the density. Compaction for the T2 condition is conducted using a 0.61 m lawn roller. The roller is packed with soil so the soil cannot move inside the roller. The resulting mass of the roller is 172.5 kg. The roller is placed at the end of the prepared soil by using an overhead crane, opposite of the drawbar pull rig (DPR). The DPR cable is drawn out to the location of the roller and attached using a hook. The DPR retracts the cable and pulls the roller across the test lane. Once the roller gets to the front tire of the vehicle, the DPR is stopped. The overhead crane is used to lift the roller to the end of the opposite test lane and the same process is repeated. This set is pictured in Figure 20.

Figure 20. The T2 terrain condition calls for compaction of the soil by pulling a lawn roller over the test lane by the drawbar pull rig [6].

3.5.2.3 T1 - Terrain Condition Preparation

The T1 terrain condition is denser than the T3 and T2 conditions at a density of 1.71 g/cc. The T1 condition is defined in Table 1. The T1 preparation starts with the preparation of the T3 condition described in Section 0. The additional compaction is accomplished using a standard 25.4 x 25.4 cm tamper. This process is illustrated in Figure 21. The starting location for tamping is shown by the green circle in the front corner of the test lane. The tamper is lifted 5-8 cm above the level of the soil, shown in Figure 22, and released to fall under its own weight onto the soil. To keep the tamping process consistent and repeatable, the user must make sure to drop the taper squarely to allow for even compaction, and to not apply any force to the tamper as it falls. The tamping pattern is shown in Figure 21, where the tamping moves from the starting location and then perpendicularly across the test lane. Each successive tamp should overlap half of the previous tamp, about 12 cm. Upon reaching the sides of the test lane, the next tamp is moved down the test lane away from the DPR, overlapping half of the previous row, and proceeding in the opposite direction. The resultant pattern is shown by the blue, black, and red squares which represent the successive rows of the tamping process. This procedure is followed for the entire test lane. To achieve the T1 condition, the test lane must be tamped with this procedure 7 times, while shifting the starting location by half of a tamp each time, which is about 12 cm.

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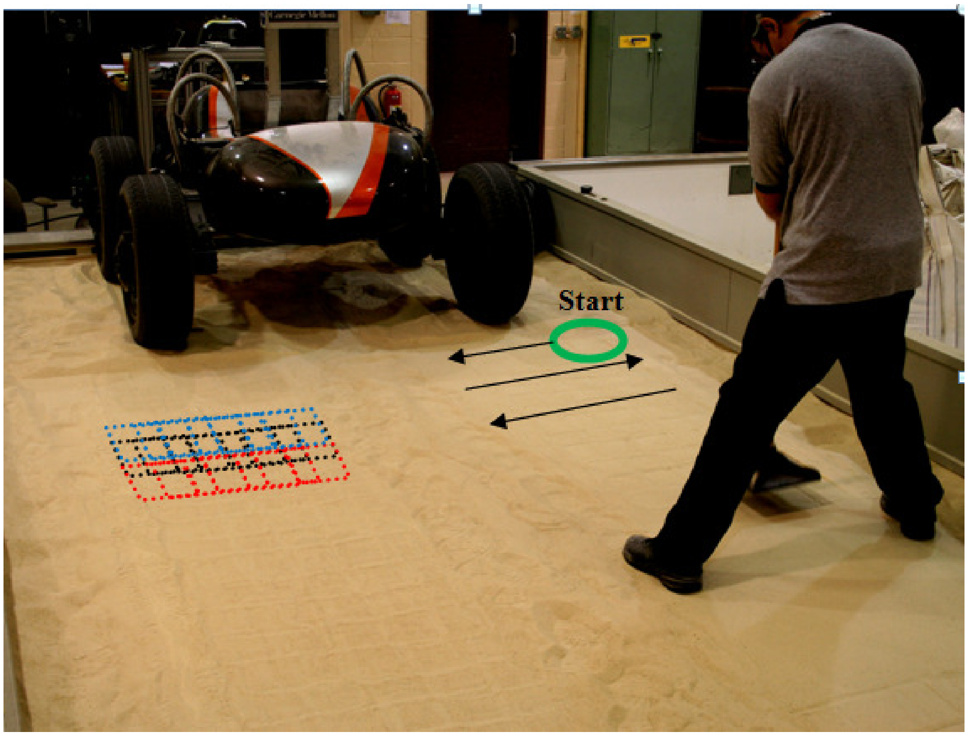


Figure 21. The tamping procedure used to prepare the T1 terrain condition. The tamping starts at the corner of the test lane and moves perpendicularly while overlapping each successive tamp by 4 inches. The resulting tamping pattern is shown on the left.

Figure 22. The tamper is lifted 5-8 inches above the soil level and dropped square and under its own weight.

3.5.2.4 Verification of Terrain Condition Using the Cone Penetrometer

Verification of the terrain condition and preparation for the tests conducted in this study was accomplished using a Rimik CP40II cone penetrometer as the measurement tool, and a statistical analysis to determine the mean and standard deviation of the cone index gradient, *G* and the linearity coefficient, α of the GRC-1 soil. The CP was equipped with a 30 degree apex angle cone tip and a base area of 323 mm^2 (0.5 in^2). The cone index gradient, in kPa/mm, is the ratio of the cone index *CI*, or force per unit area to move the aforementioned cone through the soil in kPa [12], and measurement depth, in mm. The linearity coefficient represents the linearity of the average *CI* versus depth curve [27]. This technique of using the cone penetrometer was based on the success of W.E.S experiments and Freitag's conclusion in [12] that the *G* is a sufficient measure of the consistency of the soil. For GRC-1, a measured value of *G* can be used in coordination with Figure 15 to determine the relative density, D_R of the soil at the site of the measurement. Further characterization of the terrain condition can then be deduced using *G* and D_R with the information about GRC-1 published by the Oravec, Zeng, and Asnani in [4]. The statistical method and evaluation metrics used to characterize the soil prior to a drawbar pull tests are explained in this section.

Once the soil has been prepared according to any of the terrain conditions described in Sections 0-3.5.2.3, eight CP measurements were taken along the length of the test bed. Four measurements were taken manually at the centerline of each side of the track, equidistance apart between the start and end of the preparation region, as shown in Figure 23. The CP was pushed into the soil at an approximately constant speed of 3 cm/s to a depth of at least 18 cm, where the CP records the average *CI* over each of 10 mm of depth.

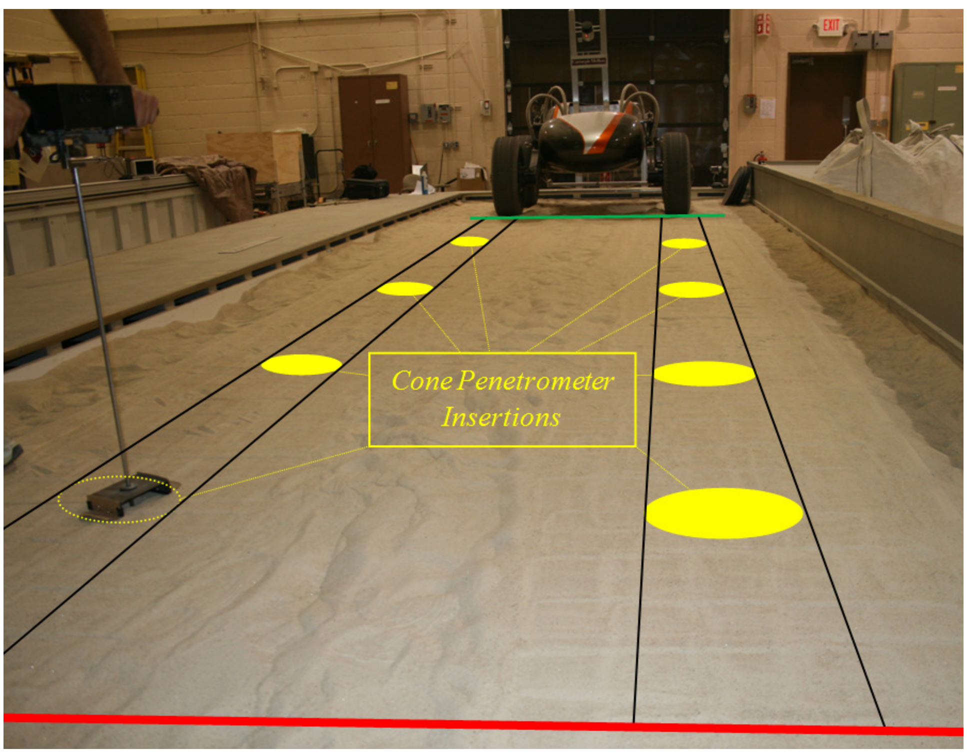


Figure 23. Eight cone penetrometer measurements are taken to assess the terrain condition prior to a drawbar pull test.

The analysis of the terrain preparation was based on three metrics, the mean and standard deviation of *G* and the linearity coefficient over a depth of 0-18 cm. The linearity coefficient is a metric describing the homogeneity of the soil with depth and represents the linearity of the average *CI* versus depth curve. The slope of this curve should be linear for a uniformly prepared dry, sandy soil like GRC-1.

The statistical analysis to verify the terrain preparation is within the defined metrics in Table 1 begins with the data from the 8 insertions of the CP. The *CI* versus depth measurements were uploaded from the CP into a spreadsheet. The value of *G* for each insertion was calculated using Equation (11) by determining the slope of the linear regression line through the *CI* versus depth measurements [27]:

$$G = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{7}$$

i = insertion number

n =total number of measurements in each data set

x_i = insertion depth (mm)

y_i = mean *CI* at a specific depth, x_i (kPa)

$\bar{x}$ = mean of x_i (mm)

$\bar{y}$ = mean of y_i (kPa)

The mean *G* for all eight CP insertions was used to describe the soil condition of the entire preparation region of the test bed where the *DP* test will be conducted. The definitions of the terrain conditions using the mean and standard deviation of *G* are shown in Table 1. The standard deviation about *G* was established by taking a large number of measurements for each terrain condition. The measurements followed a normal distribution and the standard deviations could be deduced. The relatively small values for standard deviations for the measured values of *G* for each condition indicate the soil preparations are repeatable. If the standard deviation for a prepared terrain condition was found to be outside the values in Table 1, the terrain preparation was repeated to ensure consistent conditions between tests.

The linearity coefficient, α is obtained by plotting the average *CI* versus depth curves for all eight insertions on the same plot. A 2nd order polynomial is then used to calculate a least squares fit through all 8 data sets as shown in an example plot in Figure 24. The linearity coefficient is the 2nd order coefficient, and as it approaches zero, the polynomial fit becomes more linear, or the soil is more uniform with depth. The tolerances for the linearity coefficient are shown in Table 1.

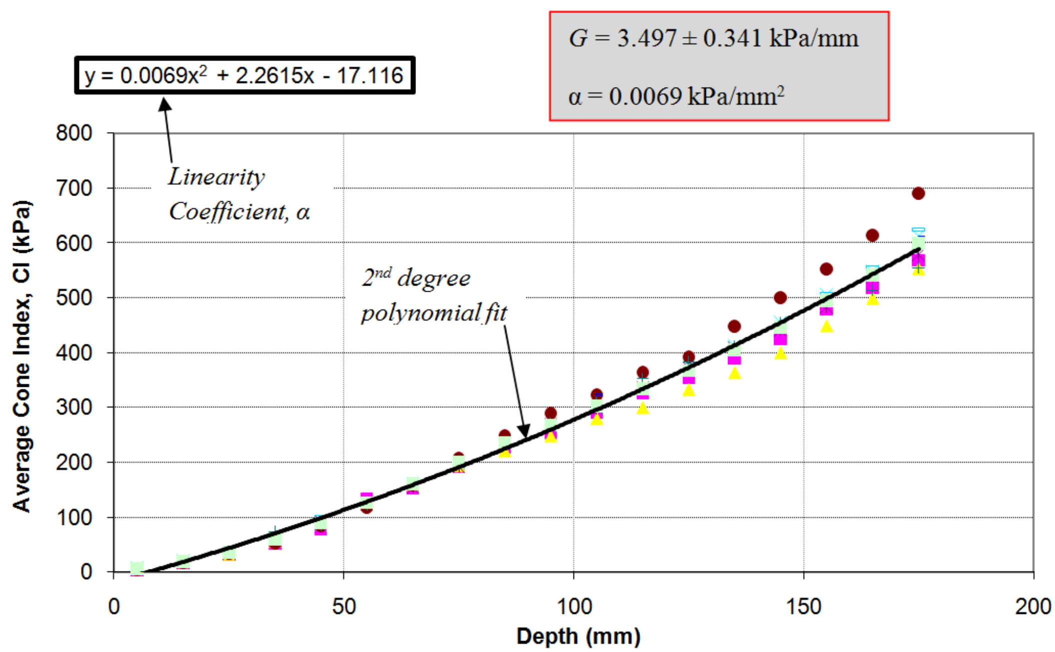


Figure 24. The average cone index (*CI*) versus depth of eight cone penetrometer insertions to measure the prepared soil. The entire data set was fit with a 2nd order polynomial and the linearity coefficient of the fit is representative of the uniformity of the soil with depth.

4. Developed Drawbar Pull Test Procedure

The drawbar pull test procedure and conventions that were developed at NASA GRC are described in this chapter. The following test procedure was developed based on the methods and techniques used by the Army Waterways Experiment Station (W.E.S), and revised based on the needs, capabilities, and goals at GRC. The subsequent sections describe the test conventions, instrumentation and measurement techniques, and the procedure of a typical drawbar pull test. Lastly, a critique of the test procedure is provided regarding the shortcomings of the test, which served as a foundation for the variation of test parameters study.

4.1 Description of Drawbar Pull Test Conventions at NASA GRC

The Simulated Lunar Operations (SLOPE) Facility at NASA GRC is capable of performing both controlled-*DP* and controlled-*TR* vehicle tests. Regarding the assessment of *DP* techniques in Section 2.2, the multi-wheeled vehicle, controlled-*DP* test techniques were selected for primary use at GRC. The controlled-*DP* technique was selected as the primary technique for conducting *DP* tests because this technique more closely resembles actual driving conditions. Other metrics, parameters, and procedures are described in the following discussion, as well their utility and justification for selection.

The zero condition selected for use at GRC was a self propelled condition on a non-deforming, non-slip surface [6]. The non-deforming, non-slip surface consisted of two strips of Nonabrasive Polyolefin Antislip Tape that were adhered to the hard floor of the SLOPE facility, as shown in Figure 25. The selection of this zero condition was based on the long established practice of using artificial surfaces for the zero condition. As stated by Dwyer in [9], “the advantage of an artificial surface is that it provides uniform and reproducible test conditions which enable valid comparisons to be made between tractors tested at different times and in different countries." The addition of the non-slip surface to the hard ground increases repeatability by helping eliminate slight inconsistencies caused by variations in the coefficient of friction between different wheels and hard surface types amongst various facilities.

Figure 25. Measuring the hard ground rolling radius on the Polyolefin Antislip Tape at GRC [6].

The rolling radius was calculated using the aforementioned zero condition, and it is defined in this thesis as the hard ground rolling radius, r_h, to clarify the zero condition [6]. The hard ground rolling radius, was calculated in conjunction with the ISTVS definition in [2], which is defined as "the distance advanced by the wheel per revolution divided by 2π." under the specified zero condition. The procedure for calculating r_h is described in Section 4.3 and in [6], and the equation is:

$$r_h = \frac{d_{ref}}{2\pi n_{rev}} \tag{8}$$

r_h = hard ground rolling radius (m)

d_{ref} = total distance traveled under the specified zero condition (m)

n_{rev} = total number of wheel revolutions

Travel reduction, as opposed to slip, was chosen as the preferred term for use at GRC [6]. The definition of *TR* from ISTVS in [2] was selected as the primary definition, being a function of velocity, and is interpreted as the reduction in vehicle velocity under operating conditions compared to the velocity operating on hard ground. Calculating *TR* as a function of velocity is useful because instantaneous *TR* can be calculated when necessary. The reference velocity under the zero condition is calculated using the hard ground rolling radius. *TR* is calculated using Equation (9) [6].

$$TR = \left(\frac{v_{ref} - v}{v_{ref}}\right) x100 = \left(1 - \frac{v}{v_{ref}}\right) x100 = \left(1 - \frac{v}{r_h \omega}\right) x100 \tag{9}$$

TR = travel reduction (%)

v = vehicle velocity under operating conditions (m/s)

v_{ref} = vehicle velocity under the specified zero condition (m/s)

r_h = rolling radius (m)

ω = wheel speed (rad/s)

While calculating *TR* as a function of velocity allows for instantaneous values to be obtained, the values are very sensitive to error due to small variations in terrain and vehicle dynamics that can significantly alter the *TR*. Sampling over a time interval to find an average velocity can help desensitize the *TR* calculation. Another approach is to derive *TR* as a function of distance by multiplying Equation (9) by time, to get Equation (10) [6]. The *TR* can then be interpreted as the reduction in distance traveled per revolution of the wheel under operating conditions compared to the distance traveled per revolution of the wheel operating on hard ground.

$$TR = \left(\frac{d_{ref} - d}{d_{ref}} \right) x100 = \left(1 - \frac{d}{d_{ref}} \right) x100 = \left(1 - \frac{d}{r_h \theta} \right) \tag{10}$$

TR = travel reduction (%)
d = total distance traveled under operating conditions per revolution of the wheel (m)
d_{ref} = total distance traveled under the specified zero condition per revolution of the wheel (m)
r_h = hard ground rolling raidus (m)
θ = total wheel rotations (rad)

Equation (10) is the typical calculation method at GRC, where the data used is generally acquired over a distance of 0.3 m. This method reduces the sensitivity of the *TR* calculation and produces repeatable results. If an instantaneous calculation of *TR* is required, Equation (9) is used.

As *DP* testing at GRC is conducted primarily for exploration vehicles, the GRC-1 lunar soil simulant was selected for testing in this thesis because the results could be applied in coordination with development of vehicles and wheels for the lunar missions in the future. GRC-1 was developed by Oravec, Zeng, and Asnani, as described in [4]. A summary and a description of soil parameters applicable for this study were presented in Section 3.5. The measurement of the density and consistency of the GRC-1 soil was performed with a cone penetrometer, according to the methodology developed by the Army Waterways Experiment

Station. The cone index gradient, *G* was the metric used to describe the consistency and density of the soil. The procedure of measuring and statistically verifying the terrain condition is explained in Section 3.5.2.4.

Over the last 50 years, many metrics have been used to describe the performance relationships among performance parameters. These were explored at GRC-1, but two specific relationships were selected for use to compare testing techniques and vehicle and wheel designs. They are the *TR-DP* relation and the *PN-DP* relation, respectively, and are described subsequently [6].

The *TR-DP* relation was selected for comparing testing techniques. The *TR-DP* curve describes the performance of a vehicle with respect to how much increasing *DP* causes the forward velocity of a vehicle to decrease. If the wheel speed is constant, the increasing *DP* causes the wheels to increasingly slip as they lose traction with the soil, and the vehicle velocity and forward progress then decreases, thus, *TR* increases. The *TR-DP* curves for a vehicle operating in two different terrains (loose and dense soil), and the regions used to evaluate the performance are illustrated in Figure 26.

The three regions are the initial slope, elbow or transition region, and the leveling off of the rapid increase of *TR* at high *DP*. The initial slope is considered the most efficient performance region, because it is the region where the *DP* is increasing rapidly with little change in *TR*. The elbow region marks the transition between the most efficient region and what is typically considered the inefficient region, where the *TR* increases rapidly with small increases in *DP*. The elbow region is generally indicates the maximum desirable driving condition, because afterward, the vehicle will significantly slow down and eventually become immobilized as *DP* is increased.

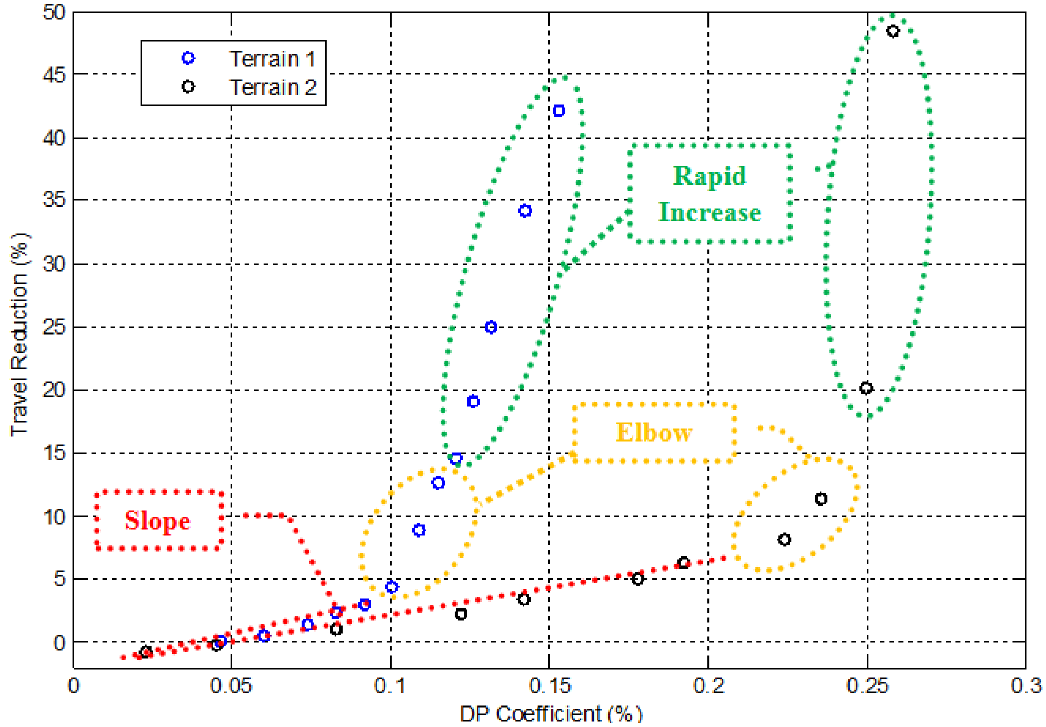


Figure 26. Example *TR-DP* relations are used at GRC to compare vehicle performance in different terrain conditions, where Terrain 1 is less dense, and using different test techniques. The important regions are the initial slope, the location of the elbow, and the region of rapid increase of *TR* at high *DP* forces.

All of the regions are used to analyze and compare vehicle performance for different purposes. Generally, the interpretation of performance is to identify the maximum *DP* before the *TR* starts to increase rapidly, and steep in the initial slope, or how quickly does the vehicle reach the maximum *DP*. For example, to compare the performance of the vehicle in Figure 26 in the two different terrains, where Terrain 1 is denser, a general analysis would be: the initial slope in Terrain 1 is steeper, suggesting that the vehicle will slow down more quickly as *DP* force is increased. The elbow region for the denser Terrain 2 is located at significantly higher *DP* than the looser Terrain 1, suggesting that significantly more *DP* can be generated in the more dense soil. Beyond the elbow region, the *TR* in Terrain 2 increases much more steeply than in Terrain 1. Hence, the vehicle will not slow down as quickly in Terrain 1 at high *DP* forces.

The *PN-DP* relation was selected for comparing vehicles with wheels. The *PN-DP* curve provides an indication of how much energy is consumed in order to generate a specific *DP*, which is extremely valuable to exploration missions as conservation of power is critical to the safety and longevity of the vehicle [6]. As an example, the *PN-DP* curves for two different tires are show in Figure 27 for the same vehicle operating in the same terrain condition.

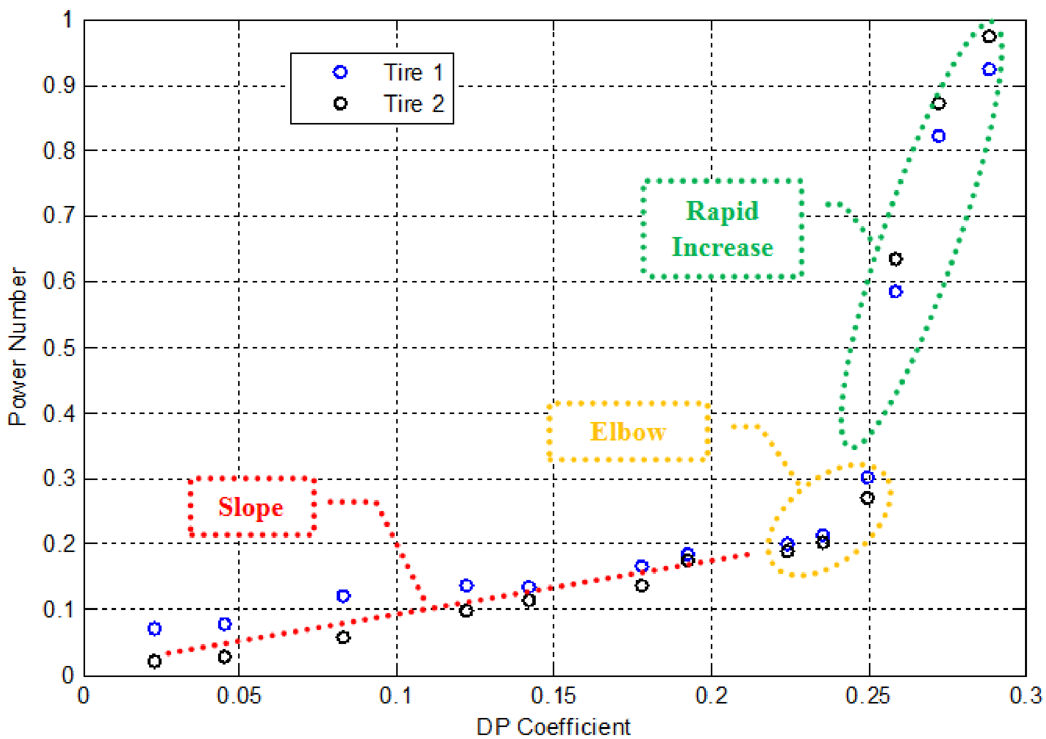


Figure 27. Example *PN-DP* relations used at GRC to compare the performance of vehicles and tires. The important regions are the initial slope, the location of the elbow, and the region of rapid increase of *PN* at high *DP* forces.

The same general regions are used to analyze the *PN-DP* curve as the *TR-DP* curve: the initial slope, elbow or transition region, and the leveling off of the rapid increase of *PN* at high *DP*. In the initial linear region, for constant wheel speed and increasing *DP*, the wheels begin to slip more, and the *TR* increases when the vehicle velocity decreases. Because the *TR* increases, it takes longer for a vehicle to travel a required distance; hence, more power is consumed and the *PN* increases. This is generally linear until the elbow performance region is reached. Again, the linear region is considered the efficient region of performance as little additional power is required to produce more *DP*. The elbow, or transition, region generally marks maximum efficient *DP*. Beyond the elbow, significantly more power is consumed to gain any additional *DP*, which is the inefficient region and is identified by the rapid increase in *PN*. At very high *DP*, the vehicle eventually becomes immobilized, but the wheels continue to spin and consume power.

An example of the analysis of the performance of the two tires shown in Figure 27 follows. Tire 2 is more efficient at generating the same *DP* as Tire 1 in the linear region, but the slope of Tire 2 is larger and as *DP*, more power is consumed as compare to Tire 1. Both tires consume approximately the same power at the elbow region and are equally efficient there. Tire 2 consumes more power than Tire 1 beyond the transition region and is less energy efficient at high *DP*.

4.2 Description of Instrumentation and Measurement Techniques

Vehicle and drawbar pull test data are collected using a combination of instruments and software. Before explaining the drawbar pull test procedure, a review of the instrumentation and measurement techniques that are used for a typical *DP* test, and for the variation of parameters experiments, is provided in this section. A summary of each measurement, the corresponding instrument used to acquire the measurement, location of the instrument, and corresponding metric is provided in Table 2 and described in more detail in this section.

Table 2. The measurements required during a drawbar pull test [6].

Measurement	Instrument	Location	Corresponding Metric
Vehicle weight (*N*)	4 floor scales	Level ground	Tire load, *DP/W*, PN
Wheel rotation (*rad*)	Rotational encoders	Wheel motors	*TR*
Motor current (*amps*)	Current meter	Wheel motors	Wheel torque, *PN*
Vehicle distance (*m*)	Rotational encoder	*DP*R drum	*TR, PN*
Drawbar pull force (*N*)	Load cell	Vehicle hitch	*DP/W*

The vehicle weight is measured by placing Scarab on four floor scales, one under each wheel. Each scale measures the respective load at each wheel so that the load distribution can be controlled. The scales measure load in real-time, so when additional weight is added, it can be balanced easily to ensure the wheel loads are equal for all wheels. Scarab is shown on the scales in Figure 28.

Figure 28. The testing weight of Scarab is checked using four scales to measure wheel loads [6].

The measurements used to calculate wheel torque and wheel speed are taken by instruments in the wheel hubs. The wheel speed of each wheel is measured by a rotational encoder and outputs the total revolutions of the wheel in *ticks*. The rotational wheel encoder *ticks* are converted to *radians* using the relationship shown in Equation (11).

$$radians = ticks \cdot \frac{2\pi}{2^{12} \cdot 400} \frac{radians}{ticks} \tag{11}$$

Where the 2^{12} is the number of *ticks* per revolution of the rotational encoder, and the total gear reduction is 400:1 [26]. The wheel torque is calculated from the motor current measured in each wheel hub by a current meter. The conversion from motor current to wheel torque is performed using constants for each wheel motor, which were obtained from calibrations where torque is measured from each wheel for a known input current.

The distance that the vehicle travels during a test is obtained from measuring the number of revolutions of the DPR drum on which the cable is wound. The drum is identified in Figure 8. A rotational encoder records the number of revolutions of the drum which is recorded as encoder *ticks* at each timestamp. The encoder *ticks* are converted to linear distance traveled by the vehicle during the test using the relationship in Equation (12). The conversion constant used to convert encoder ticks to meters is obtained from the calibration of the rotational encoder while the cable is under zero tension.

$$\text{Distance}(m) = ticks \cdot 4.4896\text{x}10^{-5}(m/tick) \tag{12}$$

As described in Section 3.2, the *DP* data was measured by a load cell attached between the DPR cable and the vehicle hitch. The data was collected and stored on Scarab's onboard computer and uploaded to an external computer. The load cell was calibrated by using an overhead crane to hang a fish scale. The load cells were hung from the fish scale, and free weights were hung from the load cell. The actual weight measured by the fish scale and recorded weight acquired by the load cell were noted, and a calibration relationship was applied to the load cell data as a first step of post-test processing.

4.3 General Test Procedure

This section describes the test procedure developed and used at GRC for a typical *DP* test. The description below includes initial setup, how the test was carried out, and the conclusion of the test.

Before conducting a *DP* test, the vehicle weight and the hard ground rolling radius, r_h were determined. The vehicle weight was measured as described in the previous section and shown in Figure 28. Calculating r_h begun by placing all wheels of the test vehicle onto a non-deforming, non-slip surface which was created by adhering two strips of Nonabrasive Polyolefin Antislip Tape to the hard floor of the SLOPE facility, as shown in Figure 25. The starting locations of all four wheels were marked on the floor by using an upside-down T-shaped tool, where the “bottom of the T” was placed against the back of the wheel and the “top of the T” was sitting flat on the ground. The corresponding location was marked by a piece of tape. The input vehicle, hard ground velocity was 0.035 m/s which corresponds to a wheel speed of 0.1 rad/s (the same wheel speed used for the in soil *DP* tests) to the end of the Antislip Tape strips. The end wheel locations were marked using the same method as marking the starting locations. The distance traveled for each wheel was measured using a measuring tape. The total wheel revolutions for each wheel were calculated from the rotational encoder data recorded by Scarab. The r_h was calculated using Equation (8).

Scarab was then positioned in the soil bin as close to the drawbar pull rig (DPR) as possible, to allow for the maximum test length of the soil bin to be utilized. The *DP* cable was attached to the load cell and then to the vehicle hitch. Once positioned to travel straight down the test lanes, the soil is prepared and verified to according to the T2 terrain condition, as described in Section 3.5.2.2.

The next step was to initialize the Scarab computer, the DPR, and other equipment. The voltage controlled current source controlling the input current to the magnetic particle clutch was energized and set to zero before the DPR was energized, so no force would be generated. This was a critical step to ensure the safety of the test equipment and personnel. The DPR is energized and the current is adjusted to apply the starting *DP* force to the vehicle, typically around 50 N, or enough to increase the tension to keep the cable taught. The predetermined *DP* forces for the test were manually controlled by the user adjusting the current. The external computer and the Scarab computer are initialized while synchronizing both of them to a stopwatch. The stopwatch is used to note regions of interest during the test. Scarab was commanded to move forward by inputting a constant vehicle speed which was enacted as a constant wheel speed. The wheel speed must be constant to ensure no accelerations occur except when the user changes the *DP* force. The selected wheel speed should be the same for all tests and generally slow to increase the amount of collected data.

A desired *DP* force during the test was kept constant for at least one wheel base of travel, the “transient region” plus an additional distance. The additional distance was called the “steady-state region,” and is illustrated in Figure 29. Within this region, the rear wheels are driving in the ruts created by the front wheels for the same *DP* force. The steady-state region is noted by recording the time on the stopwatch. The steady-state region technique was used at

GRC to simulate a vehicle traveling a long distance at a constant wheel speed and *DP* force, with the assumption that a steady-state region exists once the rear wheels are driving in the rut of the front tires. Only the data recorded in the steady-state region was used in post processing for the calculation of performance metrics. The test ends when the vehicle reaches unprepared soil, the *DP* is sufficiently large to immobilize the vehicle, or all *DP* forces have been applied and the necessary data was recorded. If desired, the rut depth can be measured as an estimate of sinkage.

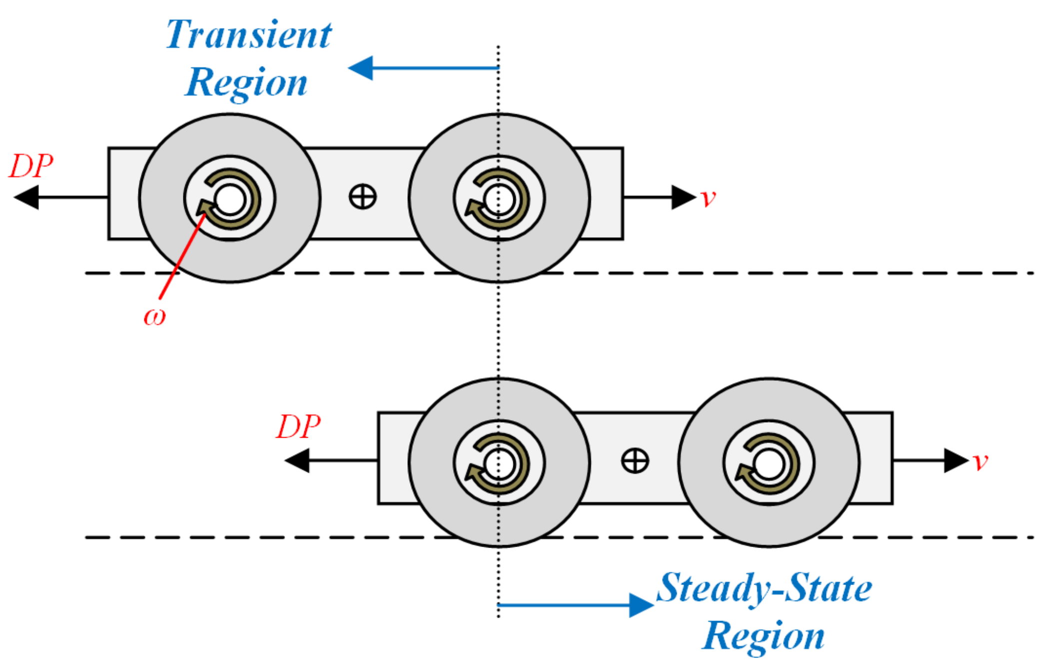


Figure 29. The steady-state region is the region where the rear wheels are driving in the rut of the front wheels created at a constant drawbar pull, *DP*.

4.4 Critique of Test Procedure and Recommendations

The techniques that formulate the test procedure at GRC were selected based on sound theory that was supported by experimental data. However, variability in the results does exist and cannot always be explained. The first step to reduce this variability is to implement more precise measurement techniques in order to minimize the systematic error. For instance, no *DP* control system exists; which seems absolutely necessary because the independent variable must be consistent and constant from test to test. Another source of systematic error all measurements are taken on the DPR or the vehicle, which is subject to vibrations. Thus, a measurement device independent of the DPR and test vehicle should be used to measure distance traveled, vehicle velocity, and sinkage. The distance traveled is currently measured by the rotational encoder in the DPR drum that rotates as the cable is drawn out. The cable was subject to minor stretching and oscillations that affect the distance measurement that significantly decreases the signal to noise ratio. While not significant for the distance measurement, the velocity was calculated as the derivative of the distance measurement and was very sensitive to the noise. An independent measurement system would not be subjected to oscillation and would allow for more precise measurements, such as a total station. A total station would be useful for calculating distance, velocity, and sinkage as it is a measurement independent of the vehicle. A total station obtains these measurements by using laser to track the distance and angle of a known point on the vehicle relative to the position of the laser.

Once a systematic error is identified and reduced, specific test parameters should be varied, while holding everything else constant, to understand how the performance of a vehicle is sensitive to the variations of different test parameters, and potentially increase the time efficiency of the test. For instance, the test procedure was developed based on the assumption that a steady-state region of performance exists. While in theory this assumption is sound, it is very time consuming to conduct tests in this manner, and the existence of a steady-state region should be evaluated considering the value of decreasing the time to conduct a test. For instance, in previous studies conducted by W.E.S in [7, 10, 12] found that the differences in performance using a constant-TR and programmed-TR (ramped-TR) techniques, for a single-wheeled *DP* tests, were insignificant. Hence, an entire DP-TR curve could be generated in one test, which is very time efficient and did not sacrifice the quality of the results. A similar investigation should be conducted that can be generalized for vehicle, controlled-DP tests.

Another test parameter to study is the effect of the soil preparation on the performance of the vehicle. The T2 condition was selected as the terrain condition to conduct *DP* tests, and it was defined based on the preparation method. While it produces a consistent and repeatable soil condition, it is not understood if the performance of a vehicle will fluctuate due to variations in soil density within the definition of the T2 condition. Therefore, a study should be conducted to experimentally determine the terrain condition that results in the most consistent performance, or define new terrain conditions based on performance repeatability.

In coordination with these recommendations, a series of studies were conducted to evaluate how the variation of test parameters would affect performance and to develop proper experiments to conduct these tests. The goals of these studies were to further develop the test procedure by indentifying sources of variability in performance; and in addition for use at GRC, that information is valuable to provide insight to the terramechanics community on how certain test parameters can affect performance. These studies are discussed in Chapters 5 and 6.

5. Variation of Drawbar Pull Test Parameters: Preliminary Studies Conducted and Their Contribution to the Development of the Final Methodology

A study of the variation of test parameters was necessary to increase the value of the developed procedure in Chapter 4, and to provide insight to the terramechanics community regarding the importance of such as study to obtaining replicable and comparable performance results. The goals of this preliminary study was to experimental identify relationships between certain test parameters and the performance of a vehicle. While this study was novel, it was necessary to develop the methodology and goals for conducting the experiments. As discussed in Chapter 2, any similar previous studies were conducted using single-wheel tests. Thus, the procedures and conclusions could only be used as a guide, but were integral to developing the hypotheses. This chapter discusses the process which was conducted to explore and identify which test parameters were most important to evaluate foremost, the development of hypotheses, the methodology to conduct the experiments, and then the preliminary experiments and results.

This information in this chapter is presented chronologically to illustrate the development of the methodology. The first study described in this chapter is determining the magnitude of performance difference while operating in the three different terrain conditions (T3, T2, T1). Next, a statistical method was developed to define the repeatability of an experiment, and to compare results by determining if they differ in magnitude in excess of the expected variability of an experiment. Then, in accordance with the recommendations made in Section 4.4, an attempt was made to determine if a steady-state region of performance, described in the Chapter 4 procedure, exists for controlled-*DP*, full vehicle tests. Finally, an attempt was to experimentally determine relationships of how variations in the density of the terrain preparation, as measured by G, affect performance. For each of these studies, the motivation, the development of the methodology and hypotheses, the experimental procedure, the results, and recommendations for improvement are provided.

Note: The chapter is termed "preliminary studies," and the results in this chapter should not be subjected to interpretation. When conducting the variation of test parameter studies, all other parameters were not held constant, specifically the test wheels and the *DP* force. The test tires were varied as these studies were initially conducted in parallel with completing other test matrices. The wheels for each study were chosen to satisfy multiple objectives. Additionally, upon the completion of this study, the drawbar pull rig (DPR) was found incapable of outputting a constant and repeatable *DP* force during and between tests, which is further explained in this chapter. Because the independent variable was not controlled, even general conclusions regarding these could not be formulated. The intent of including this chapter was to inspire future studies, further develop the methodologies and hypotheses, and to provide "lessons learned" to avoid similar problems.

5.1 Evaluation of Performance in the T3, T2, and T1 Terrain Conditions

The T2 terrain condition was chosen for *DP* testing at GRC because it was able to be consistently prepared and represented the median of the soil compaction levels measured by the Apollo astronauts on the Moon. However, the T3 and T1 conditions were also developed and also fall within the soil compaction levels on the Moon, and it was of interest to understand the differences in performance among the T3, T2, and T1 conditions. Hence, the first preliminary study was to examine the differences in performance solely based on the different terrain condition. The hypothesis was that the *TR-DP* curves for the three terrain conditions would be separated, where the vehicle would exhibit less *TR* with increasing density, which would shift the curve to the right. The three terrain conditions are defined in Table 1.

Because this was a comparative study intended for use only at GRC, the Chapter 4 test procedure was amended to be more time efficient. Instead of using the steady-state region technique, where the *DP* was increase approximately every 1.5 meters, the *DP* was increased approximately every half-meter, called the “0.5 m” technique. The 0.5 m technique was more time efficient because a full *TR*-*DP* curve was obtained in one test run. Only the data from the last 0.3 m of vehicle travel, for each constant *DP,* was used to calculate a *TR*.

This test was conducted with Scarab at the 100 kg load and equipped with the Spring Tires. The Spring Tires were chosen for this study because, at the time, they were being evaluated for implementation on lunar vehicles. Therefore, any information using these tires would be applicable for other studies. This combination of vehicle setup and terrain condition was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. The results from these tests are shown in Figure 30.

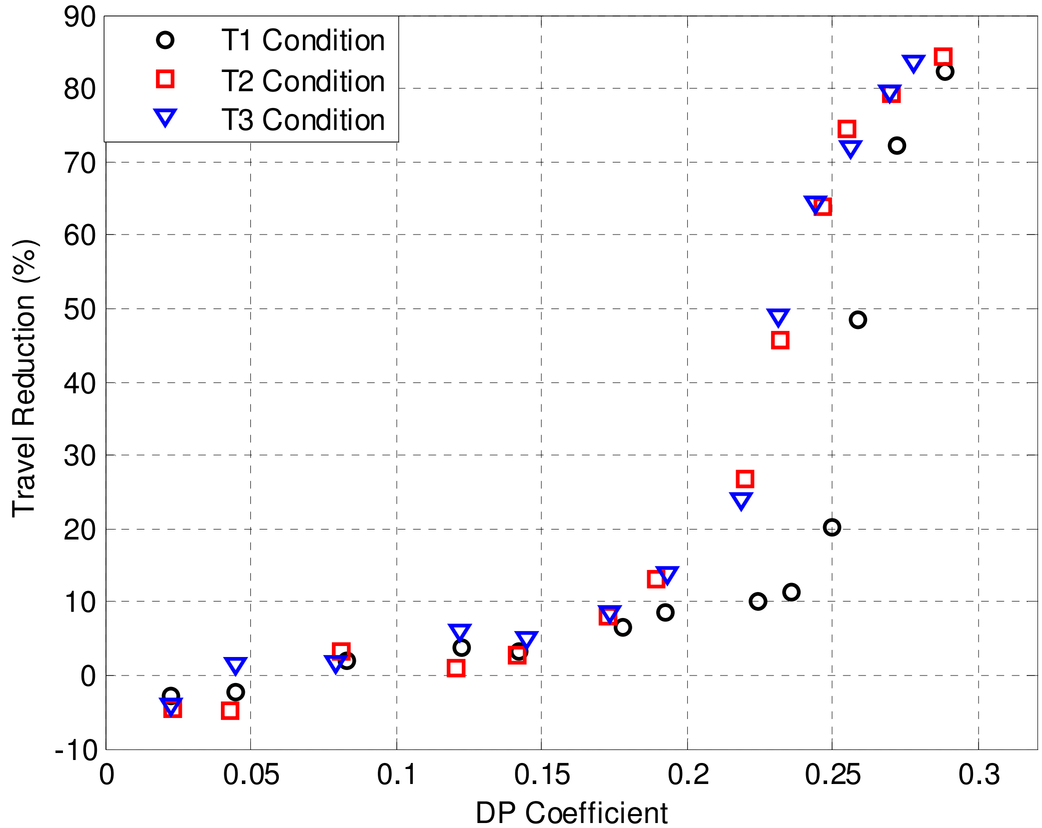


Figure 30. The results of terrain condition comparison tests with the Spring Tires. Vehicle performance in the T3 and T2 terrain conditions are similar, but the T1 condition produces less travel reduction at higher drawbar pull forces.

The results show that the *TR-DP* relations are similar for both T3 and T2 conditions throughout the entire curve, and the *TR* is less for the same *DP* in denser T1 condition. This result contradicts the hypothesis that all of the curves would be separated because the change in density would cause different *TR*. However, the fact that the cone penetrometer measurement does not account for all performance influencing soil parameters, such as surface effects, could be the cause for these results.

A repeat study was conducted to check the validity of this result. The test tires were changed to the treadless pneumatic with an inflation pressure of 1 psi to achieve a low contact pressure. The low contact pressure would limit the sinkage, reducing the effects of the density of the soil and increasing the influence of surface effects. The results are shown in Figure 31.

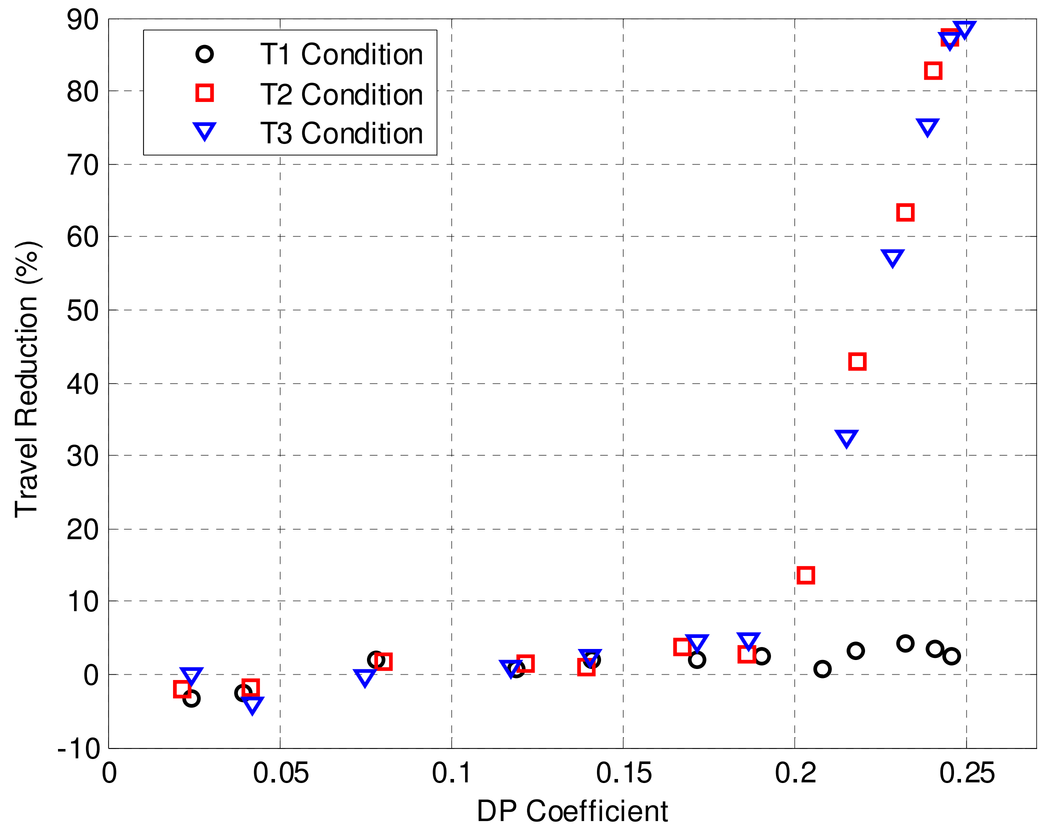


Figure 31. The results of terrain condition comparison tests with the treadless pneumatic tires at 1 psi. Vehicle performance in the T3 and T2 terrain conditions are similar, but the T1 condition produces less travel reduction at higher drawbar pull forces. The tested *DP* forces were not large enough obtain the full curve, but the separation is evident.

The results in Figure 31 show that, again, the vehicle performance in the T3 and T2 terrain conditions is similar, and the T1 condition causes significantly less *TR*. Again the hypothesis was disproved. The conclusion was that there is some relation between the density of the terrain preparation and performance such that the T3 and T2 terrain conditions produce similar results. It was evident that a future study was necessary to obtain the relationship showing how performance varies based on the density of the terrain preparation. Two such studies are described in Sections 5.4 and 6.5. For subsequent experimentation, the decision was made to use the T3 condition, because it required less time to prepare and seemed to produce the same results as the T2 condition.

5.2 Development of a Statistical Analysis to Compare and Assess the Repeatability of Drawbar Pull Tests

In Section 5.1, the 0.5 meter (0.5 m) test technique was selected because it was significantly more time efficient than the Chapter 4 procedure as only one 0.5 m test was necessary to generate a full *TR-DP* curve; whereas, the Chapter 4 procedure would require in excess of 3-4 tests to acquire the same data. However, based on the assumption that a steady-state performance region existed and the explanation in Section 4.3, the performance from 0.5 m technique was considered transient. Hence, the quality and consistency of the results were unknown. Before the technique could continue to be used, the repeatability of the technique needed to be assessed, and a statistical procedure was developed to compare and asses the repeatability of *DP* tests. This section will describe the statistical procedure, its utility, and its application to the 0.5 m test technique.

5.2.1 Statistical analysis of drawbar pull tests

The statistical analysis began with conducting five identical tests in succession. The quantity of five tests was selected considering the tradeoff between time and quality of results. Conducting five successive tests would take a significant amount of time, and considering the tradeoff between quality of result and efficiency, the time consumed to conduct more than five tests outweighed any increase in the precision of the analysis.

The data from the five repeat tests were processed to produce *TR-DP* curves, where one, discrete *TR-DP* data point was calculated for each tested *DP*. The discrete data points which form the *TR-DP* relationships then fit with a 3rd order polynomial. The residuals of *TR* relative to the polynomial fit were calculated using Equation (13) [6].

$$r_n[m] = s_n[m] - s_n^{fit}[m] \tag{13}$$

n = test number

m = data point number for a given *DP/W*

$r_n[m]$ = the residual for a given *DP/W* (%)

$s_n[m]$ = the calculated *TR* from the test data for a given *DP/W* (%)

$s_n^{fit}[m]$ = the 3rd order polynomial fit *TR* value for a given *DP*/I (%)

The standard deviation in *TR*, σ_n, for each test was then calculated using these residuals. The standard deviation was calculated according to Equation (14) [6].

$$\sigma_n = \sqrt{\frac{1}{M}\sum_{m-1}^{M} r_n^{\,2}[m]} \tag{14}$$

n =repeat test number

m = data point number for a given *DP/W*

σ_n = standard deviation in *TR* (%)

$r_n[m]$ = the residual for a given *DP/*W (%)

$s_n[m]$ = the calculated *TR* from the test data for a given *DP/W* (%)

$s_n^{fit}[m]$ = the 3rd order polynomial fit *TR* value for a given *DP/W* (%)

While the standard deviation evaluates variability of each data point from the 3rd order polynomial fit, the ensemble deviation was defined to evaluate variability between the repeat tests. The ensemble curve fit was calculated as the mean of all the repeat test curve fits, $s_n^{fit}[m]$.

The residuals between each test curve fit and the ensemble curve fit, $R_n[i]$ were calculated by Equation (15) [6].

$$R_n[m] = s_n^{fit}[m] - \frac{1}{N}\sum_{n-1}^{N} s_n^{fit}[m] \tag{15}$$

n = repeat test number

m = data point number for a given DP/W

N = total number of repeat tests

$R_n[m]$ = the ensemble residual for a given DP/W (%)

$s_n^{fit}[m]$ = the 3rd order polynomial fit TR value for a given DP/W (%)

The ensemble deviation, $\Phi(m)$ was calculated using the ensemble residuals from Equation (16) [6].

$$\Phi[m] = \sqrt{\frac{1}{N}\sum_{n-1}^{N} R_n^2[m]} \tag{16}$$

n = repeat test number

m = data point number residual for a given DP/W

M = number of experimental data points in each test

$R_n[m]$ = the ensemble residual for a given DP/W (%)

$\Phi(m)$ = standard deviation of TR for a given test, n (%)

In order to compare the results of different tests and determine if they are significantly different, "range bars" were defined. Range bars were calculate using the discrete, *TR-DP* data points from the five repeat tests, and represent the expected variability of a test technique. For each *DP* value, a range bar was defined as all of the values of *TR* between the maximum and minimum *TR*, which was calculated by Equation (17). When comparing different tests, the range bars are centered at the mean of the test results for each *DP* value. If any data point falls outside the range, it is generally considered significantly different from the rest, as it exceeds the expected variability. The conclusion that one test run was significantly different than another was made based on the frequency of a test result exceeding the expected variability.

$$RB[m] = \max(s_n[m]) - \min(s_n[m]) \tag{17}$$

n = repeat test number

m = data point number for a given DP/W

$s_n[m]$ = the calculated *TR* from the test data for a given DP/W (%)

RB[m] = the range bar for a given DP/W (%)

5.2.2 Application of statistical analysis to 0.5 meter test technique

The analysis described in Section 5.2.1 was applied to the 0.5 m test technique and is presented in this section.

The five repeat tests were conducted with Scarab at the 100 kg wheel load equipped with the Scarab rigid tires. This vehicle setup was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. After processing the raw data, the single test residuals and standard deviations, were calculated based on the 3rd order polynomial curve fits. Next, an ensemble curve fit was calculated as the mean of the five polynomial curve fits from the individual tests. The mean and the maximum ensemble deviations were calculated respective to the ensemble curve fit. The results from this analysis are listed in Table 3 and shown graphically in Figure 32.

Table 3. The standard deviations, mean, and maximum ensemble deviations for five, repeat 0.5 meter tests in the T3 terrain condition.

Metric	**Value (% *TR*)**
Standard Deviation, Test #1	1.56 %
Standard Deviation, Test #2	1.25 %
Standard Deviation, Test #3	1.71 %
Standard Deviation, Test #4	2.06 %
Standard Deviation, Test #5	1.75 %
Mean Ensemble Deviation	1.07 %
Maximum Ensemble Deviation	3.16 %

Analyzing the statistics in Table 3, the 0.5 m test technique in the T3 terrain was considered repeatable, as all the deviations are relatively small. Again, Figure 32 shows the repeat tests, the 3rd order polynomial curve fits, the residuals, and the ensemble deviation as a function of the *DP* coefficient. The ensemble deviation increases as the *DP* force increases. This was expected because the *TR* becomes more sensitive to higher *DP* forces as small changes in *DP*, soil conditions, and load distribution could affect the *TR*. Again, the maximum ensemble deviation is small and the 0.5 m test technique in the T3 soil condition was considered repeatable.

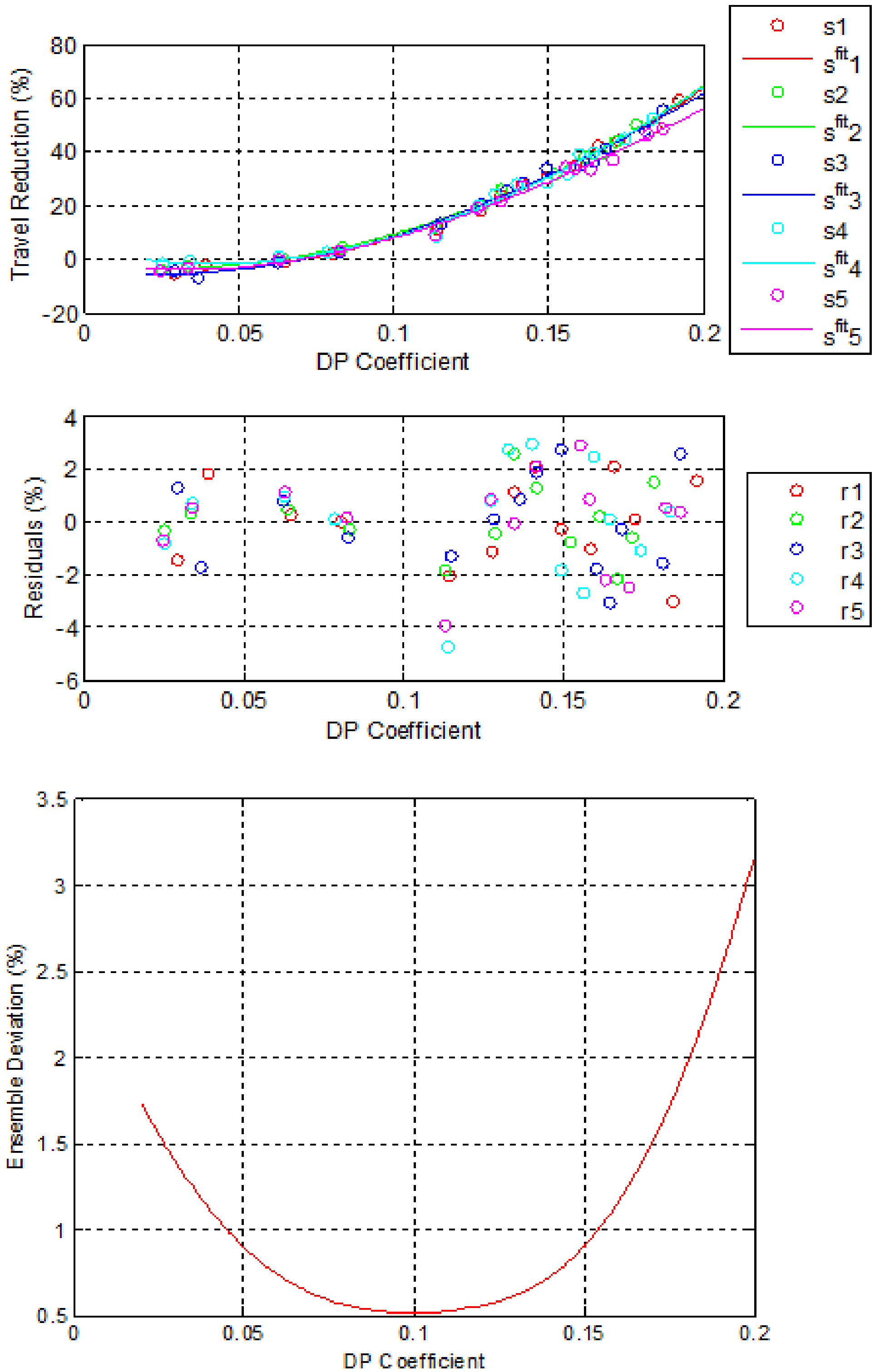


Figure 32. For the five 0.5 m repeat tests in the T3 terrain condition: (top) *TR-DP* data and curve fits for all five repeat tests, (middle) the residuals of *TR* for each repeat test, and (bottom) the mean ensemble deviation.

In addition, the range bars were calculated and overlaid on the plot of the *TR*-*DP* curves for each of the five repeat tests, and are shown in Figure 33. The method that was chosen was to depict the expected variability using the range bars. Again, the heights of the range bars were defined as all of the data points within the range of the min and max *TR* for a given *DP* coefficient. The range bars were positioned at the mean *TR* and *DP* coefficient for each *DP* coefficient. Note, as stated previously, the *DP* force was not able to be consistently controlled at this time and the scatter in the *DP* coefficients between tests is evident in Figure 33. The range bars show the expected variability of the 0.5 m test technique in the T3 terrain condition.

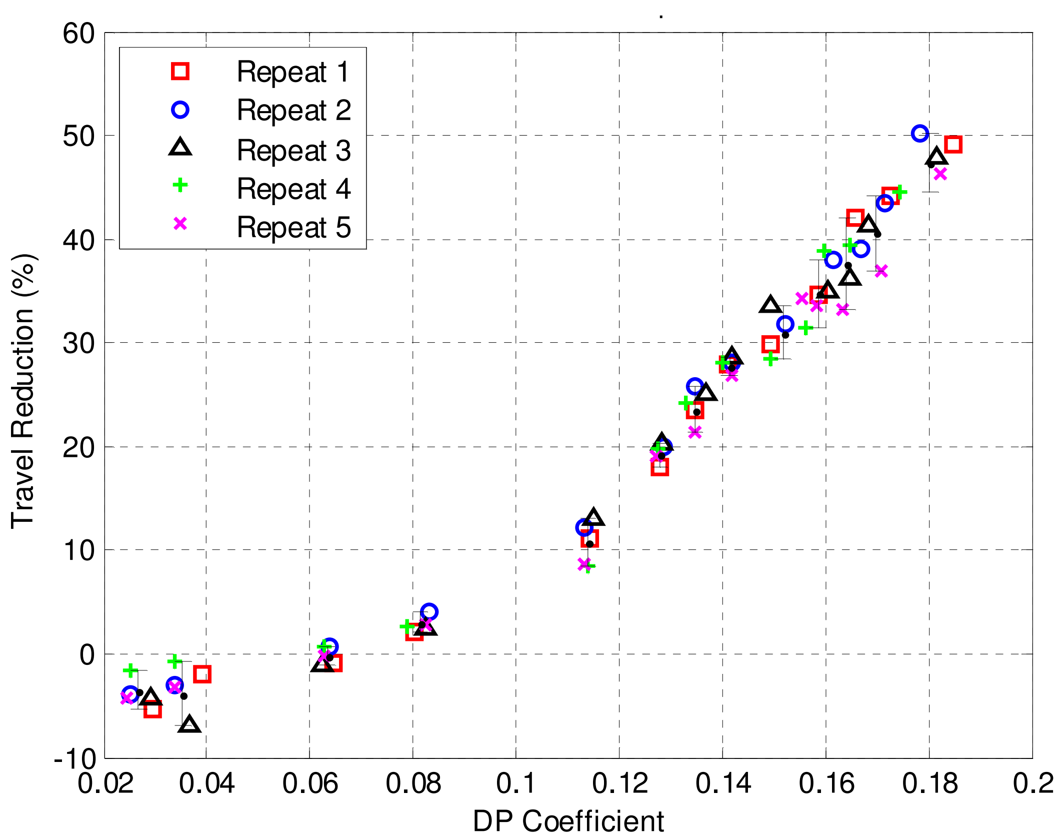


Figure 33. The *TR-DP* relation for the five repeat, 0.5 meter test in the T3 terrain conditions, complete with overlaid range bars depicting expected variability. The *DP* between tests could not be held constant due to the lack of a *DP* control system.

5.3 Identifying the Region of Steady-State Performance

As concluded in the previous section, the 0.5 m technique was found to be sufficiently repeatable and was significantly more time efficient than the Chapter 4 procedure. However, while developing the Chapter 4 procedure, the assumption was made that a steady-state region of performance existed for a vehicle operating at constant wheel speed and *DP* in a constant terrain; therefore, the vehicle performance using 0.5 m technique would be considered in the transient region. The steady-state region was defined in Section 4.3 as the region where the rear wheels operate in ruts of the front wheels under a constant *DP* and terrain condition. An explanation of the theory regarding how the performance would vary in each region follows.

According to the steady-state assumption, as *DP* increases by being stepped or ramped, the wheels will slip more and further compact the soil, creating a denser rut than the rut of the previous, smaller *DP*. When the *DP* was increased, the rear tires were still operating in the ruts of the previous *DP*, which are less dense. Therefore, in the transient region, the ruts created by the front wheels are denser than the ruts in which the rear where are operating. Once the rear wheels enter the denser ruts produced by the front wheels, the *TR* is theorized to decrease. Hence, the steady-state region would be identified at a distance traveled at constant *DP* where the *TR* significantly drops off and then remains constant. Based on this theory, the hypothesis for this study is that the *TR* will significantly decrease at some distance traveled at constant *DP* and then remain constant. This would occur most likely around one wheel base, or 1.2 m.

A review of the single-wheel, controlled-*TR* tests conducted by W.E.S in [7, 10, 12] provided insight regarding the steady-state region of performance and evaluate the validity of the hypothesis. In an attempt to simplify their test matrices, the constant-*TR* (slip) technique and the programmed-*TR* (slip), a.k.a. ramped-*TR*, techniques were compared. The constant-*TR* technique was used assuming that eventually the wheel will reach a steady-state region of performance, and the longer the vehicle travels; the more likely that it will reach this region. The entire soil bin length was used for this test, and only one, constant *TR* value was tested to measure a corresponding *DP*. A programmed-*TR*, or ramped-*TR*, is the opposite extreme. As illustrated in Figure 34, the *TR* is ramped up linearly with distance or time, and *TR* is never constant.

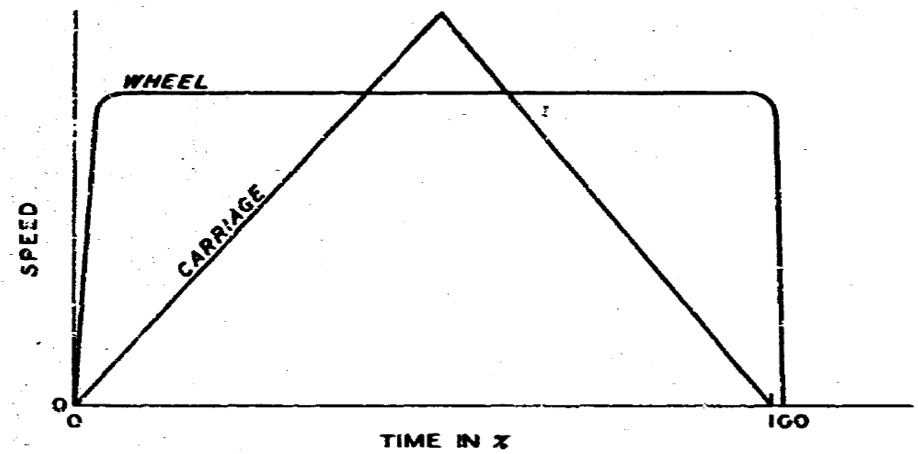
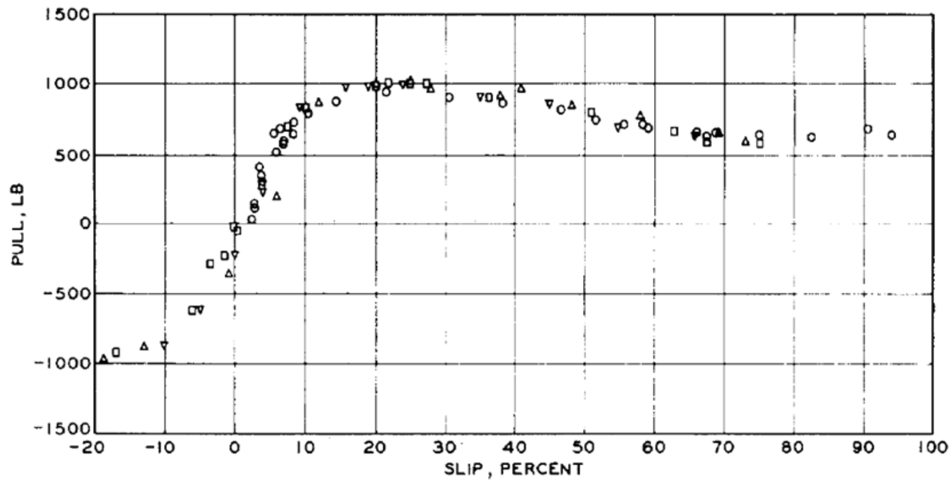


Figure 34. Wheel speed versus time for a programmed-*TR*, or ramped-*TR* test technique [12].

Considering Figure 35 from [7], the researchers at W.E.S found the insignificant differences between constant-*TR* (slip) and programmed-*TR* (slip), and concluded that "within the precision of the data, the same pull-slip relation is obtained from the programmed-slip tests as the steady-state tests" [12]. This study was insightful, but was specific to single-wheel tests, and suggested that either no steady-state region existed, or the performance in that region is not significantly different from that in the transient region.



▽ =constant slip. △ =programmed-increasing slip.
□ =programmed-decreasing slip. ○ =controlled pull.

Figure 35. Comparison of controlled-slip (*TR*) and controlled-pull methods conducted in [7].

At GRC, the tests for this study were conducted with Scarab at the 100 kg wheel load and equipped with the treadless pneumatic tires at an inflation pressure of 30 psi. This combination of vehicle setup and terrain condition was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. A variety of *DP* forces was selected. The *DP* forces were chosen to acquire data in each region of the *TR*-*DP* curve as described in Section 4.1. The T3 terrain condition was used in coordination with the conclusion made in Section 5.1. A constant-*DP* test was conducted for each selected *DP* force. Because the variation in *TR* for the entire test was desired, the average *TR* was calculated at one second intervals. The *TR* versus distance curves are shown in Figure 36.

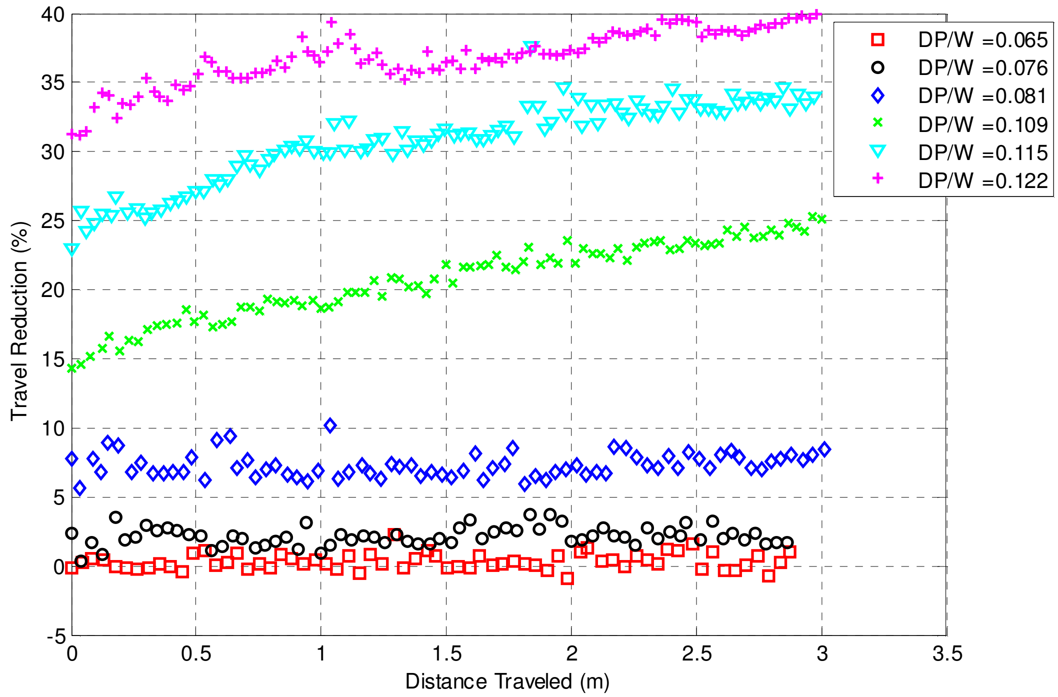


Figure 36. Travel reduction versus vehicle distance traveled at "constant *DP*/*W*" in the T3 terrain condition. *DP*/*W* was not actually constant for these tests, and the variation of *TR* seemed to follow the *DP*/*W* variation.

As shown in Figure 36, the *TR* appears to increase with distance traveled, especially at higher *DP* forces, and no significant decrease in *TR* is apparent. This suggests that a steady-state region does not exist or is not significant. However, after processing the results, the *DP* force was found to significantly fluctuate during each test, and generally increased with distance. And unfortunately, no conclusions could be drawn from this test.

As shown in Figure 37, the variations in *TR* seemed to be dependent on the *DP*. Therefore, the distinction between the fluctuating *DP* and the distance traveled could not be made. Again, no useful conclusions were drawn from this test.

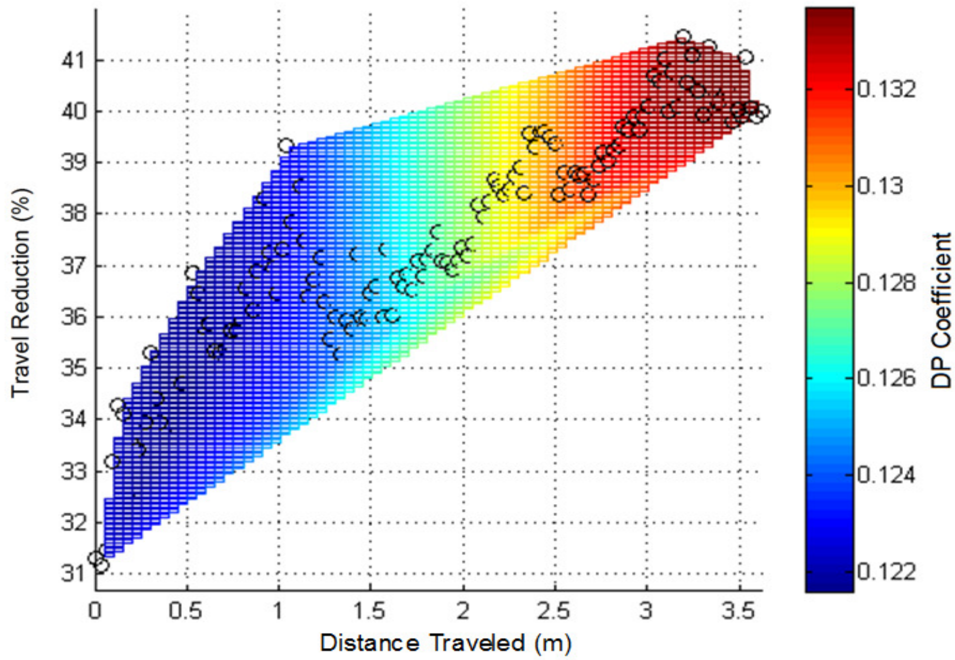


Figure 37. The variations in *TR* seemed to follow the variations in *DP*. The target constant *DP*/*W* was 0.122. No useful conclusions were able to be drawn regarding the "steady-state region" of performance.

5.4 Effects of Variations in Terrain Preparation Density on Performance

As discovered in Section 5.1, the performance in the T3 terrain condition was similar to the performance in the T2 condition. While this information as useful, a more comprehensive study was undertaken to develop "general" relationships between the terrain preparation density of the GRC-1 soil, as measured by the cone index gradient *G*, and vehicle performance. The desired relationships were considered "general" because, as stated by Godbole, Alcock, and Hettiaratchi in [16], "the cone penetrometer fails to take surface effects into consideration and bears little or no analogy with the mode of operation of the traction tyre." Hence, if the different terrain conditions consistently caused differences in overall performance, a conclusion could be reached that the terrain preparation density did affect performance.

The motivation of this study was initially to determine if performance was repeatable within the regions of density that defined the terrain conditions. However it became apparent that the results of this study could be used to determine if the time of soil preparation could be reduced by preparing a looser soil (T3 compared to T2), and if the terrain conditions should be defined based on the repeatability of vehicle performance instead of being defined by the preparation method.

As this test was novel, previous studies were not useful in developing a hypothesis. The hypothesis that was developed was in coordination with that made in Section 5.1: the *TR* would generally decrease with increasing terrain preparation density. However, the rate of this change could not be predicted.

The mean density for the different terrains was described by *G*, as it is the metric used to describe the density and consistency of the terrain preparation. As reported by Oravec, Zeng, and Asnani, the relationship between density and *G* is deterministic and can be calculated using the relationships in [4]. Hence the terrain conditions could be defined based on ranges of *G*.

Six, equally divided, terrain conditions were selected that comprised the total density range of the T3, T2, and T1 terrain conditions ($2.0 < G < 5.5$ kPa/mm), and are listed in Table 4. From a generalized perspective, this test would be conducted for the entire range of densities of interest for the testing soil

The next step was to develop preparation procedures to create each terrain condition. Each terrain condition was initially prepared according to the T3 soil condition, where the loosest condition as obtained by making sure to shovel the soil as loose as possible. Additional compaction was performed using an 8 inch square tamper.

Table 4. The terrain conditions used to develop general relationships between relative density, as measured by *G*, and performance.

Terrain Condition	Range of, *G* (kPa/mm)	Mean Relative Density, D_R (%)	Mean Bulk Density, ρ (g/cc)
R1	2.25 ± 0.25	8.02	1.62
R2	2.75 ± 0.25	14.02	1.64
R3	3.25 ± 0.25	20.01	1.65
R4	3.75 ± 0.25	26.00	1.67
R5	4.25 ± 0.25	32.00	1.68
R6	4.75 ± 0.25	37.99	1.70

A series of "practice" preparations were performed before testing to ensure each terrain condition could be achieved. In accordance with the tamping procedure in Section 3.5.2.3, the additional compaction was created by dropping the tamper from a specific height its own weight, and making a specific number of passes as listed in Table 5.

To increase the precision of the terrain preparation verification analysis, each terrain condition was measured with sixteen cone penetrometer insertions (instead of eight) and then verified using the statistical method described in Section 3.5.2.4. This preparation method was developed so the terrain conditions could be repeated consistently for each successive test.

Table 5. Tamper drop height and number of passes to obtain the desired GRC-1 terrain conditions.

Terrain Condition	Tamper Drop Height (cm)	Number of Passes
R1	no tamping	-
R2	3-5	1
R3	5-8	2
R4	5-8	3
R5	5-8	5
R6	5-8	7

The procedure for testing in these terrain conditions was to conduct a constant-*DP* test, and for each test run, three of the terrain conditions were prepared, where each terrain condition was of 1.5 m in length. Therefore, only two test runs were needed to test a constant *DP* in each of the six conditions. Four *DP* forces were selected to conduct this study, where each *DP* would capture a different region of the *TR*-*DP* curve, as described in Section 4.1.

The three terrain conditions were prepared from loose to dense along the test bed; hence, for one test the order was R1, R2, and R3, and the next test was R4, R5, and R6. The test vehicle was Scarab under a wheel load of 100 kg and equipped with treadless pneumatic tires at an inflation pressure at 30 psi. This vehicle setup was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. A constant-*DP* test was conducted for each run. The *TR* was calculated using only the data from the last 0.3 m vehicle travel in each terrain condition, and the results from this study are shown in Figure 38.

Although minor trends were apparent, no useful conclusions could be made from these results because the *DP* force could not be held constant during a test and between tests. Figure 39 shows the *TR* versus *G* for the target $DP/W = 1.09$. It was obvious from examining Figure 39 that the *DP* force was not constant during and between tests, and the variations in *DP* force masked any changes in *TR* due to changes in terrain preparation. Again, no useful conclusion could be drawn from these results.

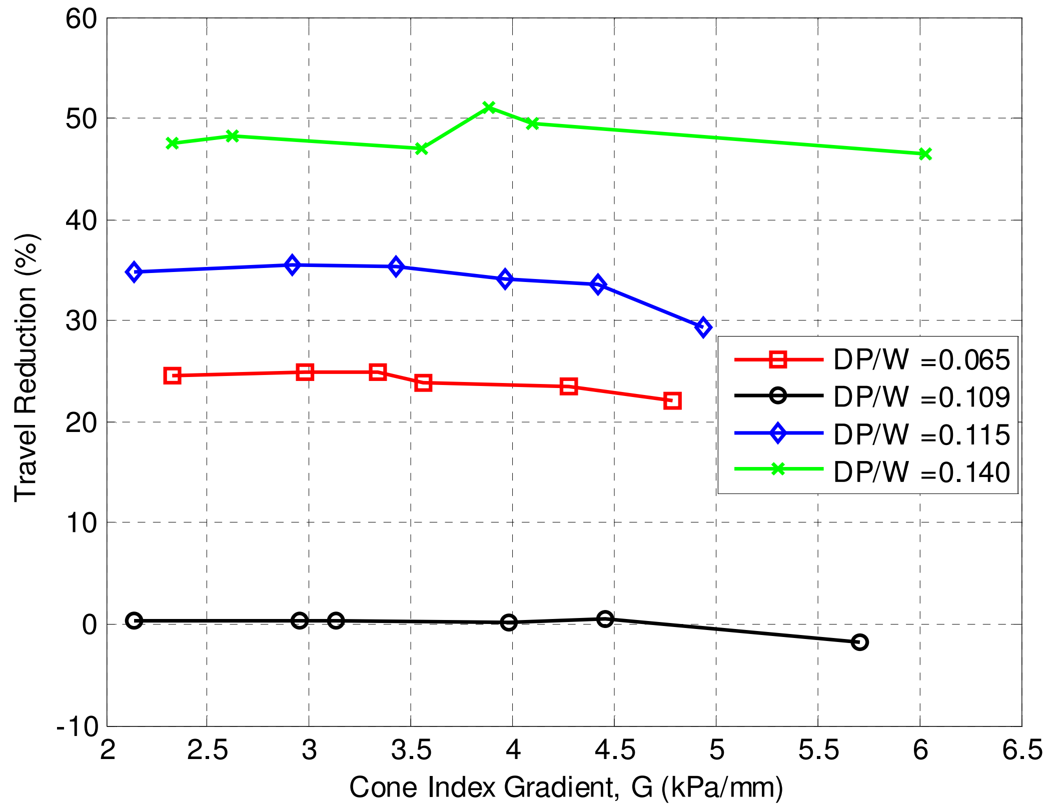


Figure 38. The *TR* versus *G* relations for various *DP* forces. The *DP* force was unable to be held constant during the test and between tests, and the *TR* trends could not be distinguished from changes in *DP*. No useful conclusions could be drawn from this study.

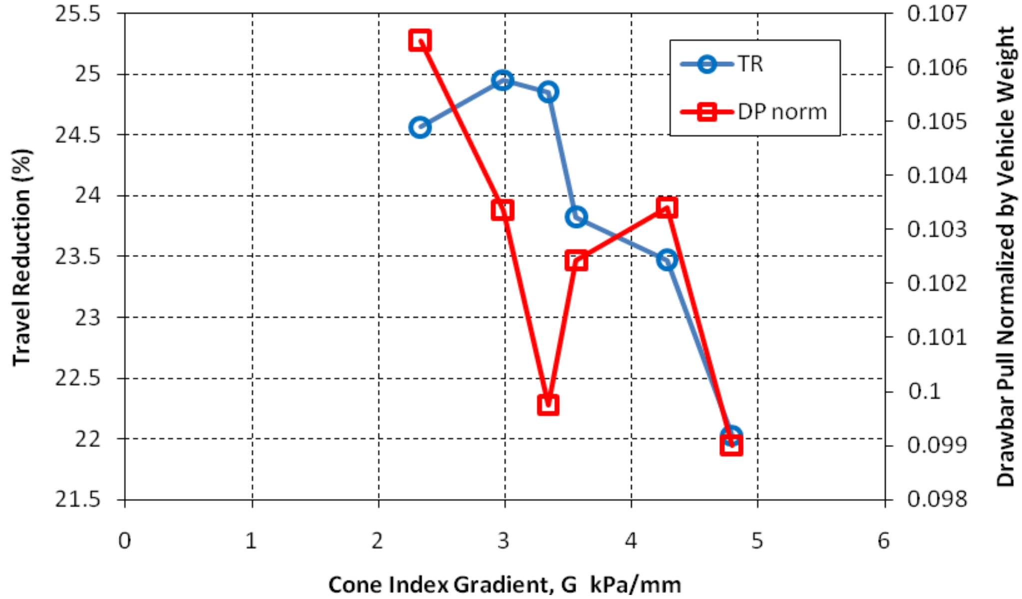


Figure 39. The trend between *TR* and *G* was masked by the effects of variations in *DP* force.

5.5 Conclusions and Recommendations

Studying how varying testing parameters affect the vehicle performance for controlled-*D*, vehicle tests is important to understand the sensitive of the performance and to identify ways to avoid them; it also has the potential to increase the economic efficiency of conducting extensive studies. Unfortunately, at the time these preliminary studies were conducted at GRC, the *DP* force was unable to be controlled or held constant during and between tests. Therefore, no conclusions were drawn regarding the steady-state region of performance, and no trends could be discerned relating vehicle performance and average density of a terrain preparation. Hence, the respective hypothesis could not be proved or disproved.

However, the vehicle performance using the 0.5 m test technique in the T3 terrain conditions was found to be repeatable, and a statistical procedure was developed to analyze future tests. While not entirely successful, these studies provided motivation and the basis for further testing, and also provide lessons learned to avoid such mistakes in the future.

A very important lesson learned was that a study should not be conducted until the independent variables can be precisely controlled. The *DP* force must be controlled to ensure that the *DP* can be held constant during a test and the same *DP* can be applied between tests. Before future testing is conducted, an active control system must be implemented to the DPR at GRC. This active control system should communicate with the load cell measuring the *DP* force and be able to adjust the current input to the magnetic particle clutch at a high frequency to keep the force constant. In addition, the control system should allow for a test to be programmed, where the DPR automatically conducts a test consisting of a variety of *DP* forces.

Investigating if a steady-state region of performance exits is extremely important to the economic efficiency for *DP* testing. While evaluating if a steady-state region exists is valuable, a more useful study to evaluate the length at which a vehicle should travel at a constant *DP* is to compare the ramped-*DP* technique to different "stepped-*DP*" techniques. A stepped-*DP* test is a general term including both the 0.5 m technique and the Chapter 6 technique, where the *DP* is "stepped" up at according to a specified length of vehicle travel. By comparing these techniques and determining the expected variability of *TR* described in Section 3.5.2.4, any significant differences in performance, dependent on the length of vehicle travel at constant *DP*, could be discerned. Also, an assessment of the existence of a steady-state region could be made. The goal would be to determine the minimum required length of travel that would maximize the amount of *DP* forces that could be applied during a single test run, without sacrificing repeatability, and not cause significant differences in performance.

Also important is a continued study to develop trends between the densities of the terrain preparations and resulting performance. The T2 and T3 terrain conditions were defined by the method of preparation and seem to produce the same performance results. If this is always true, the faster to prepare, T3 condition, should be used for *DP* testing in GRC-1. Assuming that the aforementioned trend can be experimentally proved, and is significant, a implied conclusion would be that the testing terrain conditions should not be defined based on preparation method, but rather on the repeatability of the performance of the vehicle in that terrain condition.

These preliminary studies reinforced the value of their results to the development of *DP* testing at GRC and to the terramechanics community. While they were conducted in parallel with other motives present, a revised and more precise study was conducted following these preliminary studies and is described in Chapter 6.

6. Variation of Drawbar Pull Test Parameters: Revised Methodology and Conclusive Studies

The studies in Chapter 5 were generally inconclusive because the *DP* force could not be controlled or held constant during a test or between tests. The primary task before attempting another variation of parameters study was to implement the proposed, active *DP* force controller. Once the controller was in place, revised variation of parameters studies were conducted. The methodologies in Chapter 5 were refined, and the experience led to all of these studies in this chapter to be conclusive.

Once the *DP* control system was implemented, the repeatability of the 0.5 meter test technique was repeated to redefine the expected variability and repeatability metrics. An additional parameter was identified as important, and it was necessary to investigate if the consistency of the starting terrain condition affected the ultimate performance of the vehicle. Then, the revised studies of how the performance of a vehicle varies with distance traveled and the density of the terrain preparation are discussed. Finally, the conclusions and recommendations are provided. The data for the tests in this chapter are located in the Appendix.

6.1 Implementation of the Proposed Active Drawbar Pull Control System

The DPR was designed assuming it would hold a constant *DP* force according to an input current; however, the DPR was found incapable as proved in Chapter 5, and an active *DP* control system was implemented to ensure that the force would be held constant. The controller chosen was an Opal-RT HIL Box real-time controller which is capable of providing feedback and control at a rate of 1 KHz [28].

The control system inputs are a load cell, attached to the hitch on the rear of the test vehicle, and the rotational encoder located inside the cable drum inside the DPR. The signal from the load cell, pictured in Figure 40, travels through an amplifier and then to an analog input of the HIL Box controller. The HIL Box controller communicates with an external computer. The control system outputs an analog signal to a voltage-controlled current source. The current is sent to the magnetic particle clutch, which dictates the magnitude of torque transferred from the motor to the cable drum [28].

Figure 40. The load cell was connected between the cable pulley and the vehicle hitch. The load cell was used to measure and control the drawbar pull force.

Software on the external computer acts as the user controlled interface. The software programs used are Opal-RT controller software and Simulink (Matlab). The Opal-RT controller software is used to initialize the controller and to acquire data from the load cell and rotational encoder, and to output an analog signal to the voltage-controlled current source. A proportional integral (PI) controller with a feed forward component is programmed in Simulink. The desired application of *DP* forces for a test was programmed into Simulink. During the test, the control system reads and stores the *DP* force from the load cell, and modifies the current at the magnetic particle clutch at a frequency of 1 KHz to follow the desired *DP* force program. The *DP* force and time stamp are compiled and stored on the computer upon the completion of the test.

6.2 Repeatability of the 0.5 Meter Test Technique

The active *DP* force control system was implemented to the DPR, and it was necessary to reanalyze the repeatability of the 0.5 m test technique. The 0.5 m technique was defined as holding a constant *DP* for 0.5 meters, and using only the data from the last 0.3 meters of vehicle travel for each *DP* in the calculation of *TR*. The same statistical analysis and test procedure was conducted as described in Section 3.5.2.4. Five identical tests were conducted using the 0.5 meter technique where Scarab was the test vehicle under a 100 kg wheel load and equipped with treadless pneumatic tires with an inflation pressure of 30 psi. This repeat study was conducted in the T3 terrain condition, because it required the least amount of time to prepare compared to the T2 and T1 terrain conditions, produces the most notable *TR,* and, as presented in Chapter 5, it was found to produce repeatable results. This combination of vehicle setup and terrain condition was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle.

In coordination with the results found in Section 5.2.2, the statistical results in Table 6 show that 0.5 m test technique in the T3 terrain was repeatable, as all of deviations are relatively small. The standard deviations, mean, and maximum ensemble deviations are shown in Table 6.

Table 6. The standard deviations, mean, and maximum ensemble deviations for five, repeat 0.5 meter tests in the T3 terrain condition, with the implemented, active *DP* control system [6].

Metric	Value (% *TR*)
Standard Deviation, Test #1	1.06% *TR*
Standard Deviation, Test #2	0.74% *TR*
Standard Deviation, Test #3	0.56% *TR*
Standard Deviation, Test #4	0.77% *TR*
Standard Deviation, Test #5	0.84% *TR*
Mean Ensemble Deviation	0.96% *TR*
Maximum Ensemble Deviation	1.86% *TR*

The variability of *TR* is considerably smaller than the previous results shown in Table 3; hence, the implementation of the active *DP* control system seems to decrease the variability in *TR* during a test and between tests. Figure 41 shows the repeat tests, the 3rd order polynomial curve fits, the residuals, and the ensemble deviation as a function of the *DP* coefficient. Again, the ensemble deviation increases as the *DP* force increases and was expected because the *TR* becomes more sensitive to higher *DP* forces as small changes in *DP*, soil conditions, and load distribution could affect the *TR*.

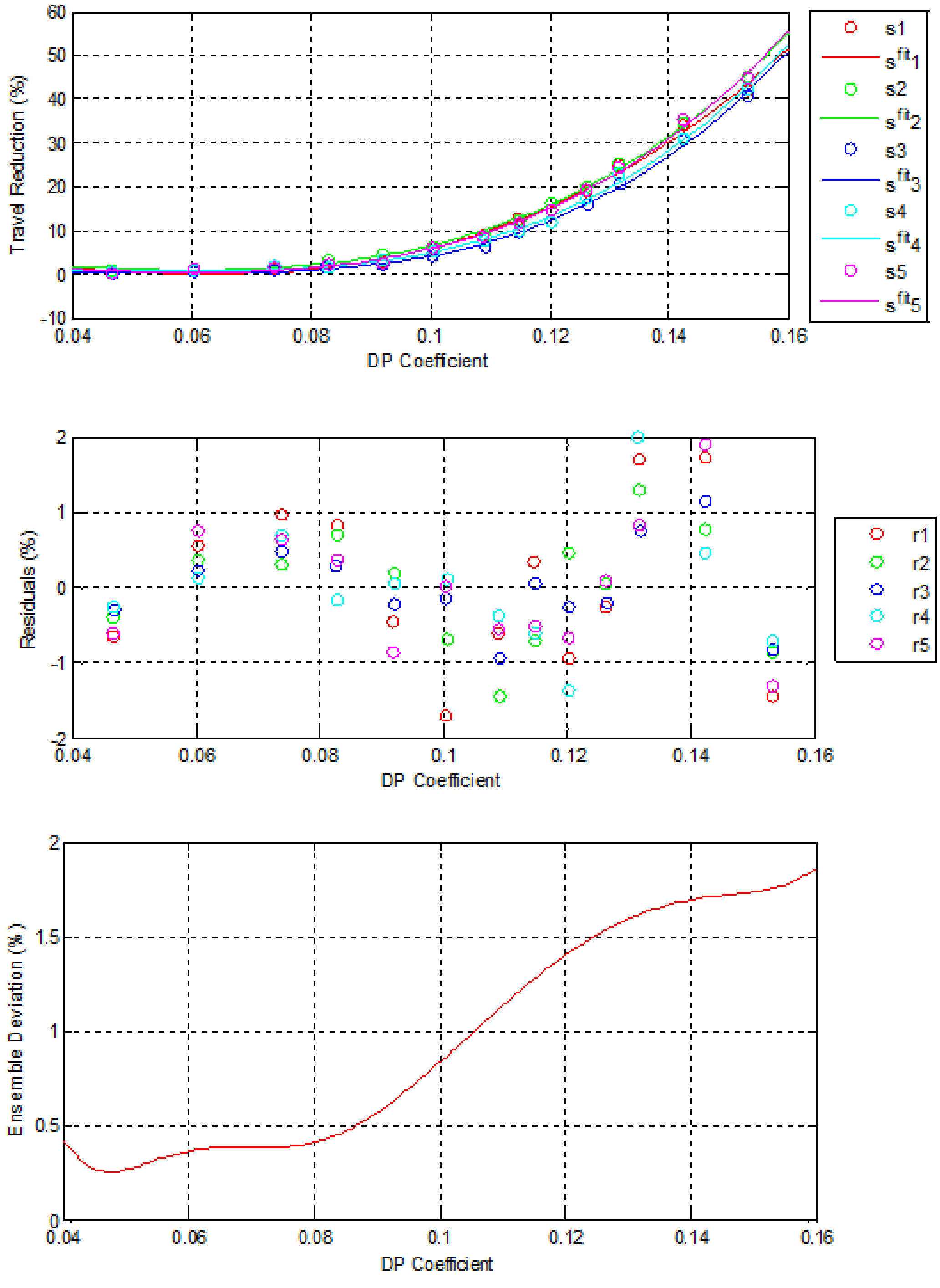


Figure 41. For the five 0.5 m repeat tests in the T3 terrain condition with the active control system: (top) *TR*-*DP* data and curve fits for all five repeat tests, (middle) the residuals of *TR* for each repeat test, and (bottom) the mean ensemble deviation [6].

The 0.5 m test technique in the T3 terrain condition was considered repeatable, and because the combination was more time efficient than the Chapter 6 procedure, it would be used for the subsequent studies in this chapter.

In addition, the range bars were calculated as defined in Section 5.2.1 and overlaid on the plot of the *TR*-*DP* curves for each of the five repeat tests, as shown in Figure 42. The heights of the range bars were defined calculating the difference between the min and max *TR* for a given *DP* coefficient. The range bars were positioned at the mean *TR* and *DP* coefficient for each *DP* coefficient. Note, as stated previously, the *DP* force was not able to be consistently controlled at this time and the scatter in the *DP* coefficients between tests is evident in Figure 33. The range bars show the expected variability of the 0.5 m test technique in the T3 terrain condition.

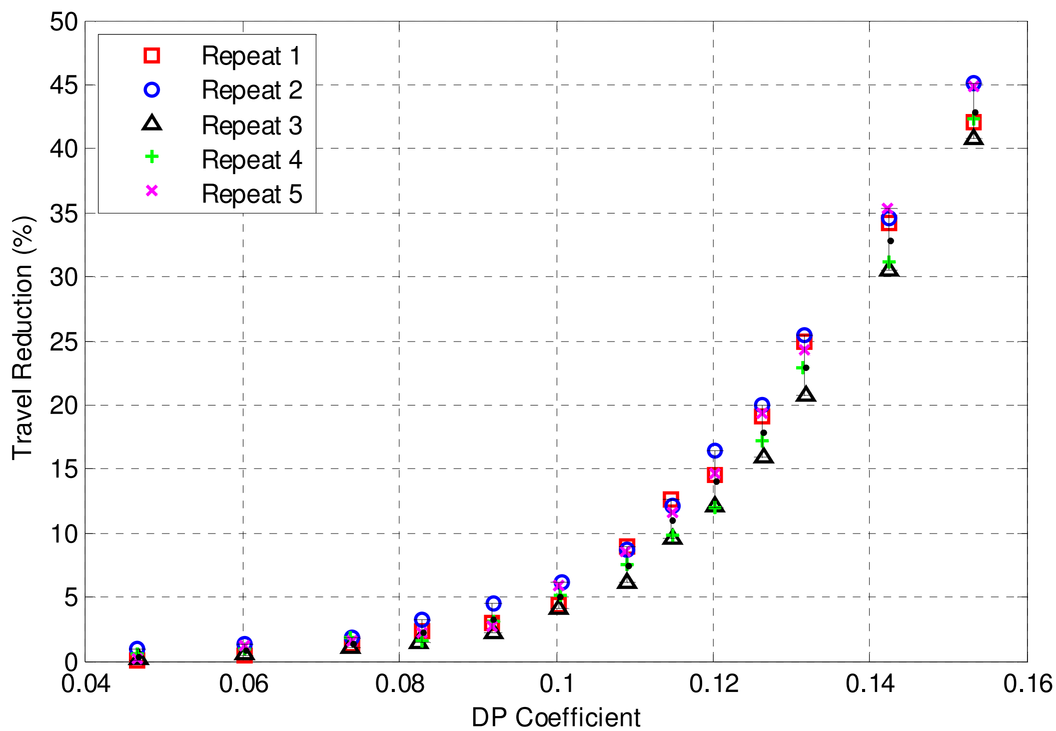


Figure 42. The *TR*-*DP* relation for the five repeat, 0.5 meter test in the T3 terrain conditions, complete with overlaid range bars depicting expected variability.

6.3 Effects of Starting Terrain Condition on Performance

While it is evident that the terrain condition affects the performance of a vehicle, it is uncertain if the condition of the terrain on which a *DP* test is started, or the "launch pad," will affect the resultant performance. The typical starting condition for a *DP* test using the procedure described in Chapter 4 was to position the vehicle at the end of the soil bin as close to the DPR as possible. The soil was generally packed from frequent traffic and walking, but was occasionally prepared and leveled. Therefore, it was important to understand if the terrain condition of the starting area had an effect on the resulting performance of the vehicle during a *DP* test, and denote if the inconsistency of the starting terrain condition could have affected past results and how significantly. The goals of this study was to determine if a specific starting terrain condition should be used for every test, and how different starting terrain conditions would affect the ultimate performance of vehicle.

A similar study was conducted at W.E.S by Murphy and Green in [7]. For controlled-slip (*TR*), single-wheel tests, three testing surfaces were used as the starting condition: the wheel resting on a nonyielding surface, resting on the prepared soil, and embedded 10-11 inches in the soil. For the latter two starting conditions, the desired *TR* was attained within 2-3 feet of travel. The conclusion was that "when the selected slip was achieved, the wheel performance adjusted accordingly and essentially reached the same equilibrium values, whatever the initial condition."

While this study was insightful, it was not necessarily applicable to full vehicle, controlled-*DP* tests. In coordination with the conclusions in [7], the hypothesis for this study was that the starting terrain condition would not affect the resulting performance of the vehicle. The test of this hypothesis was conducted using the range bars as calculated in Section 6.1. By positioning the range bars at the mean of the *TR* data for each respective *DP* coefficient, if the *TR-DP* curve for any test falls consistently outside of the range bars, it would be considered significantly different from the other tests. Otherwise, it would be within the expected variability of a single 0.5 m test in the T3 terrain preparation.

The preparation of each starting terrain is described along with the test procedure. The results and recommendations for this study are discussed thereafter.

6.3.1 Starting Terrain Preparation and Test Procedure

Four starting terrain conditions were used in this study to represent the extremes of possible starting terrain conditions, a non-yielding surface and burying the wheels in the soil, and the conditions in between that are frequently used for testing at GRC, a previously trafficked dense terrain and a prepared T3 terrain condition.

The non-yielding surface was created by placing two wood boards on the soil, as pictured in Figure 43. The typical starting condition was a previously trafficked, dense terrain, where the wheels were in the ruts of the previous runs. This starting condition was created by conducting this test after many previous tests, without preparing the terrain, and is pictured in Figure 44. The buried condition was used to simulate the extreme of high, initial sinkage and is pictured in Figure 45. The wheels were buried 10-12 cm below the level of the soil. The final starting condition was a prepared T3 terrain condition. Scarab was gently placed on the prepared soil using an overhead crane. For each of the starting conditions, the vehicle travels 1.2 m, or one wheel base, before the rear tire reaches the prepared terrain.

Figure 43. Scarab starting on the nonyielding surface, which were two wood boards.

Figure 44. The typical starting terrain condition was a previously trafficked and dense soil.

Figure 45. The wheels were buried 10-12 cm below the level of the soil to achieve the buried starting condition.

For all of the tests, the test vehicle was Scarab with a 100 kg wheel load and equipped with the treadless pneumatic tires at an inflation pressure of 30 psi. The soil bin was prepared to the T3 terrain condition. This combination of vehicle setup and terrain condition was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. The test technique was a 0.5 m test, where an entire *TR-DP* curve could be generated in one test run.

6.3.2 Results and Recommendations

The results from the starting terrain conditions tests are shown in Figure 46. For each of the tests, once the rear wheels reached the prepared soil, the vehicle had completely recovered from the starting terrain condition, as the sinkage was approximately the same. For all of the starting terrain condition tests, the *TR* for each respective *DP* coefficient is within the expected variability as denoted by the range bars. Hence, the change in the starting terrain condition did not cause any of the tests to fall outside of the expected variability of a single test. The hypothesis was confirmed, and the conclusion of this corresponds with that mention before from [7]. The starting terrain condition did not affect the resultant performance of the test. The vehicle will recover from the starting condition, and once this occurs, the performance will not be affected.

Considering the results from this study, the starting condition does not affect the ultimate performance of the vehicle during a *DP* test, and no additional time should be spent preparing the terrain of the starting location in the test bin.

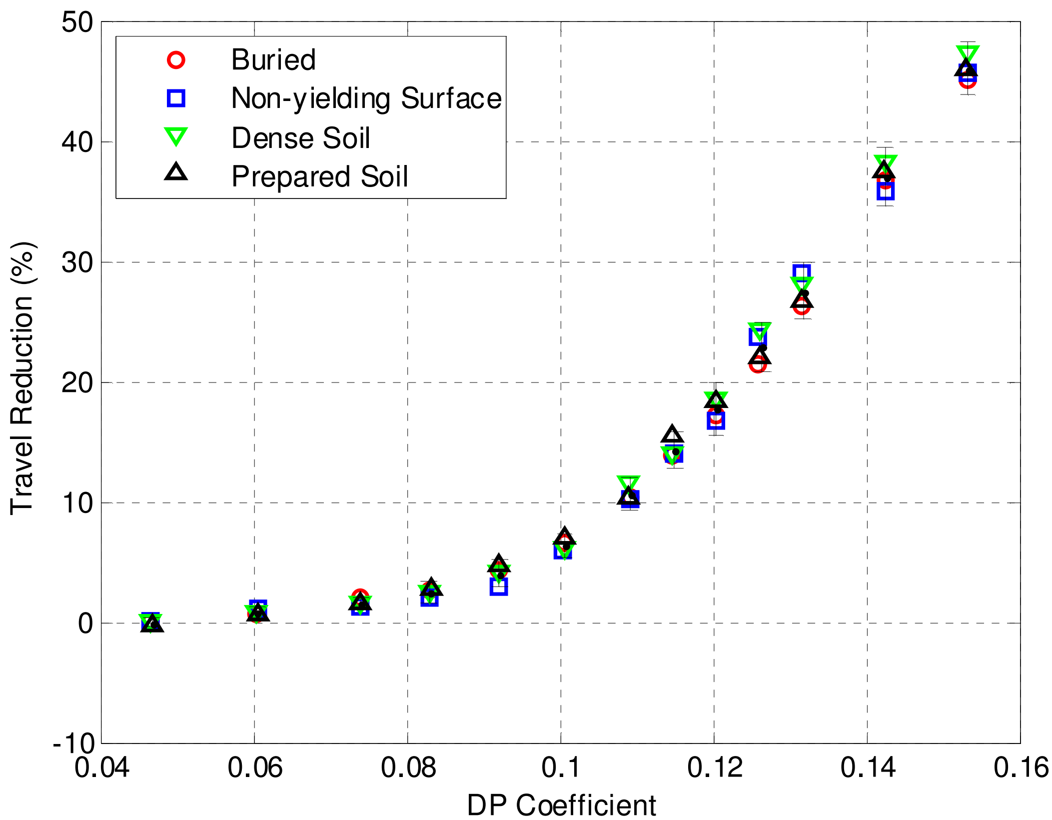


Figure 46. The *TR-DP* curves for the different starting terrain condition tests. The range bars show that the variations in *TR* for each respective *DP* coefficient are within the expected variability of the 0.5 m test technique and in the T3 terrain condition.

6.4 Effect of Distance Traveled at Constant Drawbar Pull on the Performance of a Vehicle

The purpose of evaluating how distance traveled at constant *DP* affects performance was originally to identify the region of steady-state performance, as described in Section 5.3. While the identification of the steady-state region was still important and desired, the methodology was revised to be more applicable to procedural level techniques. Specifically, the ramped-*DP*, stepped-*DP*, and constant-*DP* test techniques. Hence, instead of varying the *DP* force and evaluating how the *TR* varies with distance, the distance traveled was made the test parameter that was varied. The results would then be more representative of how the variation of distance traveled by the vehicle at constant *DP* and in a constant terrain would affect the performance of the vehicle. With this revised methodology, both the optimal testing distance techniques could be determined as well as if a steady-state region exists.

The 0.5 m, stepped-*DP*, test technique was found to produce repeatable results in both Sections 5.2.2 and 6.1. However, the assumption made in developing the Chapter 4 procedure was that once the rear wheels entered the ruts created by the front wheels at a constant *DP* and terrain condition, the performance of the vehicle would be in a steady-state region. As the wheel base of Scarab was 1.2 m, the performance using 0.5 m technique would be considered transient, and was expected to produce a larger *TR* than in the steady-state region. With this assumption, the steady-state region would be identified by this significant decrease in *TR*. While this was the previous hypothesis made in Section 5.3, a further review of literature revealed that similar studies conducted at W.E.S in [7, 10, 12] concluded that the extremes of transient and steady-state performance, the ramped-*TR* and constant-*TR* techniques respectively, did not differ outside the expected variability of the test, which contradicts the steady-state assumption. However, these studies were conducted only with single wheel tests and were not necessarily applicable to full vehicle tests. Nevertheless, they provided experimental evidence that the steady-state region of performance was negligible or non-existent; and with this evidence, it was most practical to revise the hypothesis and prove that distance traveled did affect performance. If distance traveled did not affect performance and no steady-state region existed, then the most time efficient test technique should be used to increase the economic efficiency of conducting *DP* tests. Hence, the revised hypothesis was that the length that a vehicle travels at constant *DP* will not significantly affect the resultant performance, and none of the test techniques will significantly differ from the others.

In this chapter, the description and procedures for the constant-*DP*, stepped-*DP*, and ramped-*DP* are explained. Then, the comparison of the test technique results and recommendations are discussed.

6.4.1 Description of Test Techniques and Procedures

A description and procedure for each of the constant-*DP*, stepped-*DP*, and ramped-*DP* test techniques are explained in this section. The test vehicle for all tests was Scarab under a 100 kg wheel load and equipped with the treadless pneumatic tires inflated to 30 psi. The T3 terrain condition was used for all tests. This combination of vehicle setup and terrain condition was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle. The effects of the soil on the vehicle performance was especially important to this study because the steady-state region of performance was defined based on the rear wheels operating in the ruts created by the front wheels at constant *DP*.

The constant-*DP* test technique was conducted by driving the vehicle 4.8 m, or four wheel bases, at a constant *DP* force. The 4.8 meters is approximately the entire useable length of the soil bin. A single test run was required to test each desired *DP* force, and only the data last 0.3 m vehicle travel distance were used to calculate the *TR*.

Four different stepped-*DP* tests were conducted, defined by the length of vehicle travel at a constant *DP* force. A stepped-*DP* test consists of increasing the *DP*, keeping it constant for a specified distance of vehicle travel, and then "stepping" the *DP* force up to a new magnitude. Figure 47 is an illustration of the stepped-*DP* test techniques. The tests techniques were 0.5 m, 0.8 m, 1.0 m, and 2.4 m. Under the "steady-state region" assumption made in Chapter 4, the performance using the 0.5 m, 0.8 m, and 1.0 m test techniques would be considered transient. The performance using the 2.4 m test technique would be considered steady-state. Only the data from the last 0.3 m of vehicle travel were used to calculate the *TR*.

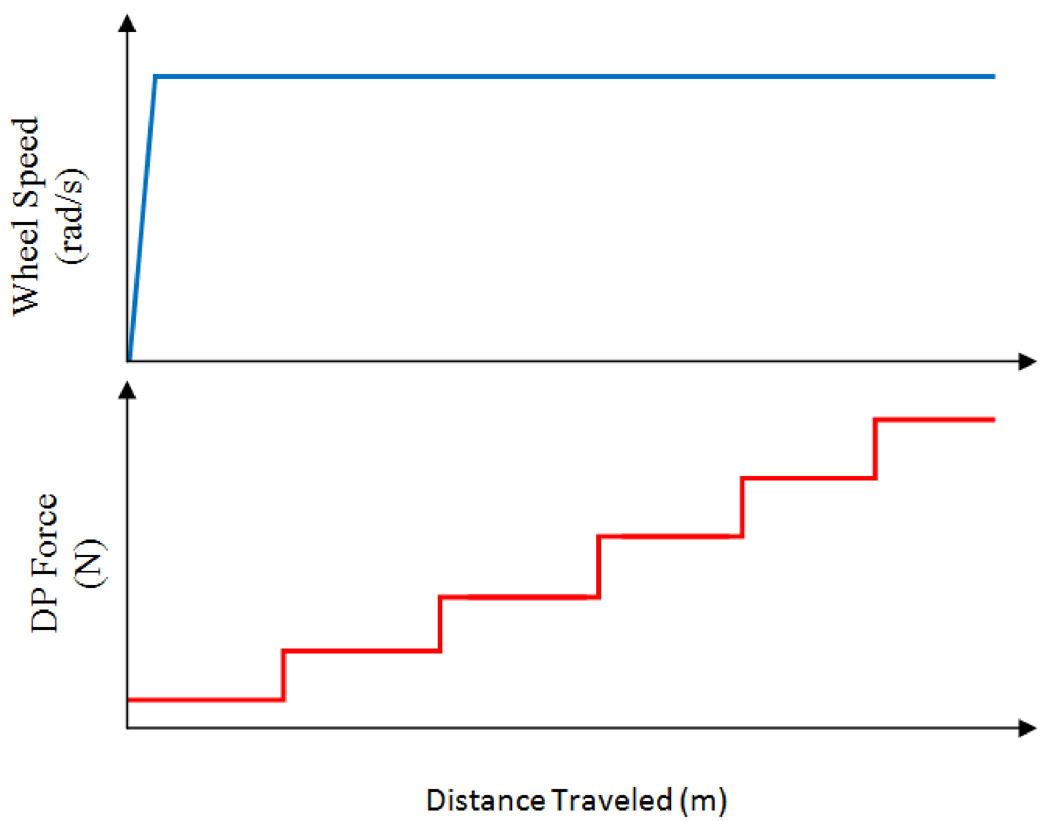


Figure 47. The stepped-*DP* test technique, where the *DP* force is held constant and then increased at predetermined distance intervals.

The ramped-*DP* test technique consisted of linearly increasing the *DP* force with travel distance, at a specified rate. For this study, the rate of increase was chosen as 62.25 N/m (14 lbs/m). Figure 48 illustrates the ramped-*DP* test.

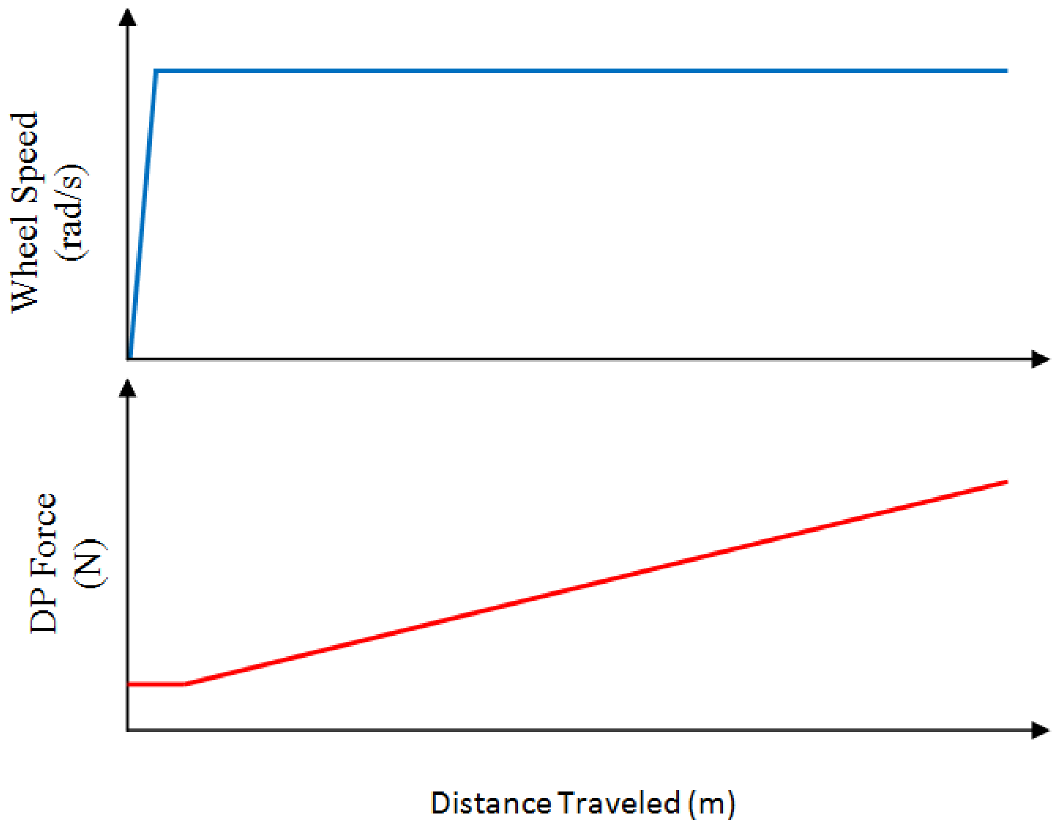


Figure 48. The ramped-*DP* test consists of linearly increasing the *DP* force with distance at a specified rate.

Calculating the *TR* for the ramped-*DP* tests was complicated because the vehicle decelerates as the *DP* increased. The measured distance traveled by the vehicle during the time of the test is shown in Figure 49. First, revisiting Equation (5), the acceleration term on the left side of the equation is not zero, and the inclusion of the inertial force will reduce the *DP*; the inertial and resistance forces must be overcome, which subtracts or "uses" the *DP* that would be available if the vehicle does not accelerate. Second, Equation (9) must be used to calculate instantaneous *TR* for the ramped-*DP* tests, because the velocity of the vehicle is not linear as the

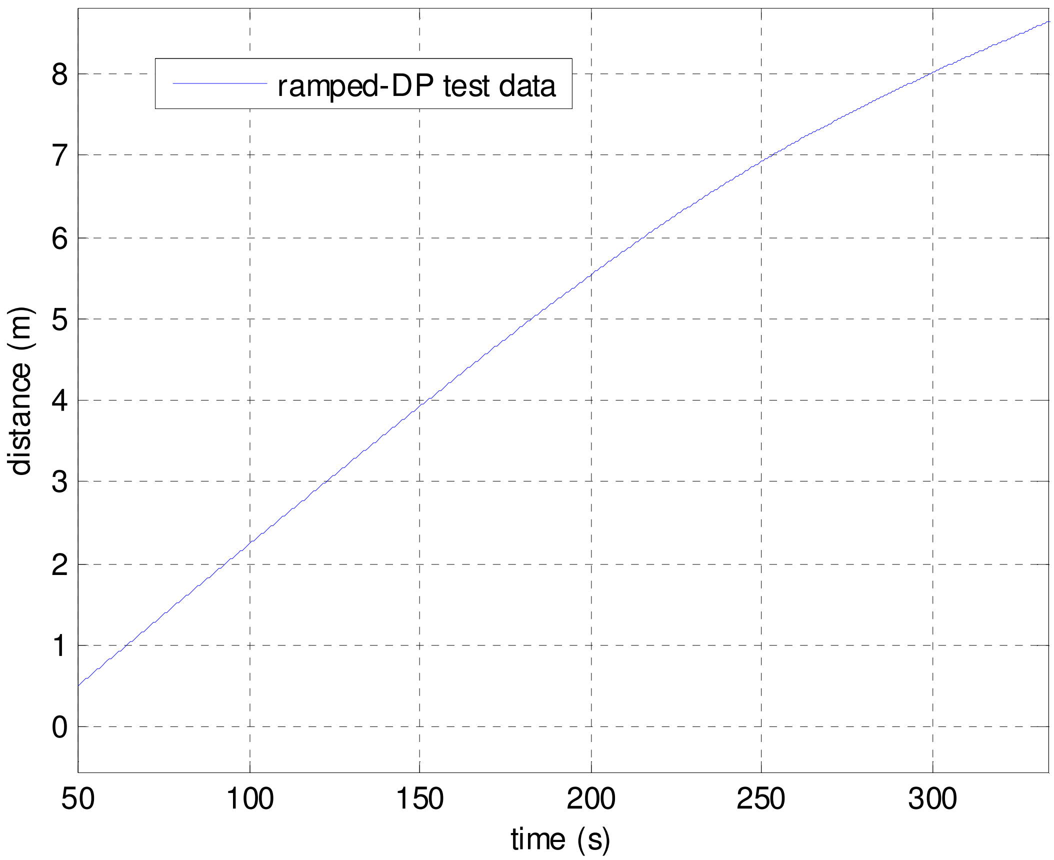


Figure 49. Distance traveled by the test vehicle over the time of a ramped-*DP* test.

DP is constantly increasing. Therefore, a time span to average the velocity could not be used because the relationship between the linear *DP* and vehicle velocity is not linear. In addition, at the time of these tests, the vehicle velocity was not measured, but was calculated as the derivative of the distance measurements, and was very sensitive to small variations in the distance measurements.

These problems were overcome by investigating the change in distance over time of the vehicle during the tests. Figure 49 is zoomed in and illustrated in Figure 50, and shows that the velocity can be approximated as linear over 0.05 m increments. Both the velocity and *DP* were averaged over the 0.05 m increments at the midpoint. Using this approximation, the inertial forces were assumed to be zero and would not affect the *TR* calculation. The *TR* was then calculated using Equation (9).

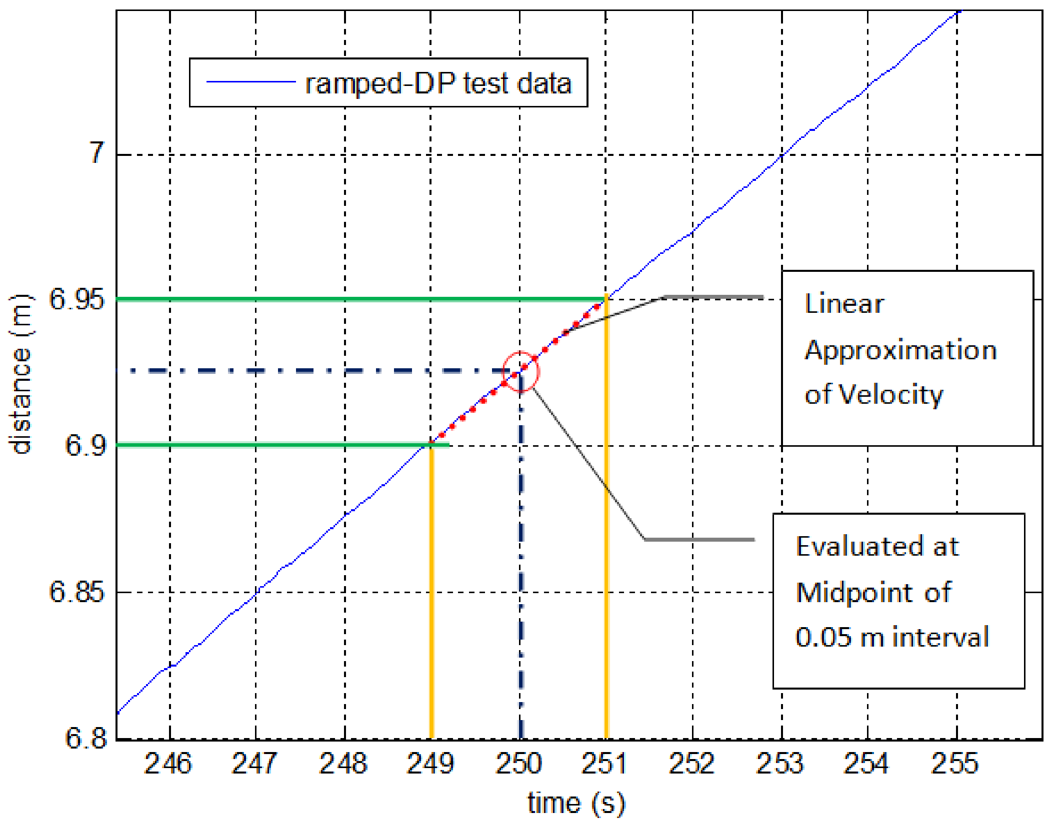


Figure 50. To calculate *TR* for the ramped-*DP* tests, velocity was approximated as linear over 0.05 m increments and averaged around the midpoint.

6.4.2 Results and Recommendations

Figure 51 shows the *TR*-*DP* relations for the constant-*DP*, stepped-*DP*, and ramped-*DP* test techniques. The hypothesis for this study was that distance traveled would not affect the performance, and that none of the test techniques would produce significantly different results compared to the other test techniques. Therefore, if all tests are the same, they should all fall within the expected variability of the 0.5 m test technique, as denoted by range bars calculated from five repeat tests, described in Section 6.1. The test of the hypothesis was conducted in this manner. The range bars calculated in Section 6.1 were positioned at the mean of the scatter of *TR* among the tests for each tested *DP* force. The results and overlaid with the range bars are shown in Figure 51.

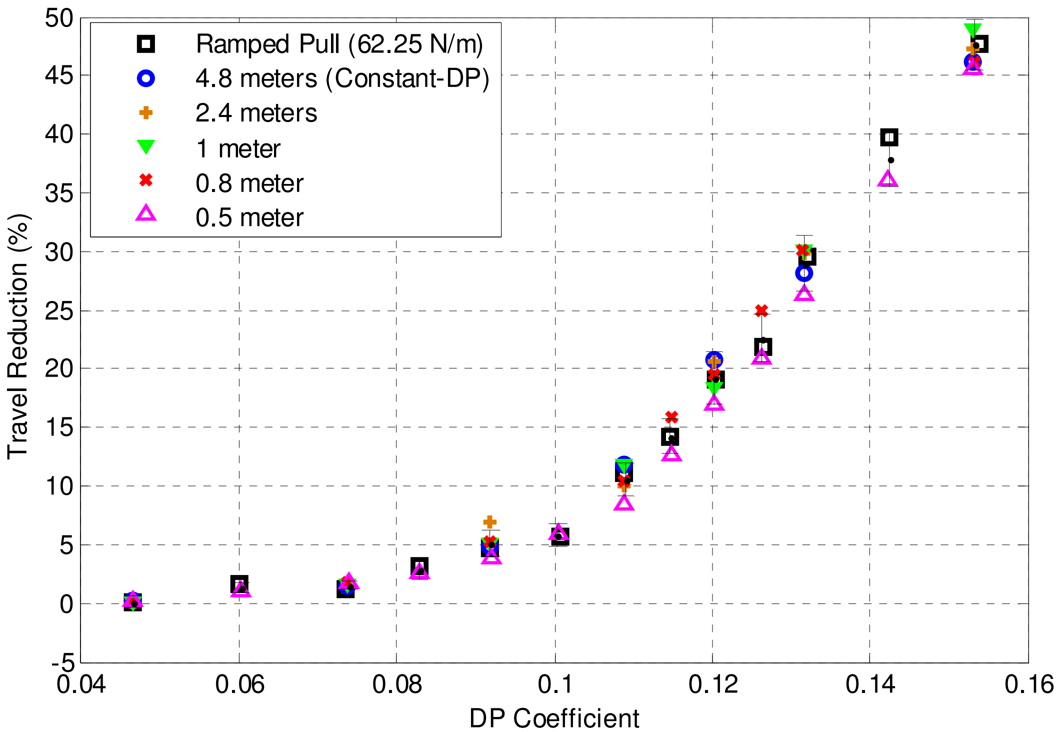


Figure 51. Comparison of the *DP*-*TR* relations for the ramped-*DP*, stepped-*DP*, and constant-*DP* test techniques.

For the most part, the *DP-TR* relations for all of the techniques fall within the range bars at each *DP* coefficient. The data scatter does not appear to fall within a specific pattern and appears random, suggesting that the variability was due to random error and not due to the testing technique. Also, the ramped-*DP* test generally falls within the middle of the other test techniques, suggesting that inertial effects at slow wheel speeds (0.1 rad/s) is not significant, and that the linear approximation of velocity was acceptable. It is evident that none of these tests were significantly different from the others; hence, the hypotheses was confirmed in that variations in distance traveled at constant *DP* does not have significant influence on the performance of the vehicle.

With respect to the aforementioned conclusion, the identification of the steady-state region of performance was necessary to evaluate to make an appropriate recommendation for which test technique to use. The steady-state region was defined in Section 4.3 as the region where the rear wheels operate in ruts of the front wheels under a constant *DP* and terrain condition. Again, the developed theory was that when the rear wheel reaches the ruts of the front wheels, the performance was considered transient, and the steady-state region would produce less *TR* as compared to the transient-region. As *DP* increases by being stepped or ramped, the wheels will slip more and further compact the soil, creating a denser rut than the rut of the previous, smaller *DP*. When the *DP* was increased, the rear tires were still operating in the ruts of the previous *DP*, which are less dense. Therefore, in the transient region, the ruts created by the front wheels are denser than the ruts in which the rear where are operating. Once the rear wheels enter the denser ruts produced by the front wheels, the *TR* is assumed to decrease. Hence, the steady-state region would be identified at a distance traveled where the *TR* significantly drops off and remains constant. However, it was more practical to prove that this theory was correct rather than test that it was not. Hence, as stated earlier, the revised hypothesis for this study is that the *TR* at any distance traveled will not be significantly different from the other distances traveled and the steady-state region of performance was negligible or non-existent.

Additional results for this study are plotted in Figure 52 as *TR* versus distance traveled by the vehicle at various constant *DP* forces. It is important to note that the data used to calculate *TR* was only from the last 0.3 m of vehicle travel. For example, the 4.8 m, constant-*DP* technique, the vehicle travels 4.5 m and the data used in the calculation is from 4.5-4.8 m. Again, as the hypothesis for this test was that there will be no significant differences in *TR* with distance traveled, and the expected variability was denoted by range bars as calculated from the repeat 0.5 m tests. From Figure 52, it appears that the *TR* with respect to travel distance at all of the constant *DP* forces, that all of the data generally falls within the expected variability. While there appears to be an increasing trend from the 0.5 m distance to the 0.8 m distance, the results for this data are generally still within the expected variability; therefore, without further testing, no explanation can be made regarding if it is a trend. No other trends appear significant in this data as the remainder of the curves appears to be random in shape, and the significant decrease in *TR*, which would represent the transition to a steady-state region, is not apparent. While, more tests are necessary to confirm if the small increase in *TR* from 0.5 m to 0.8 m of travel distance was a trend, it is clear that after 0.8 m, *TR* was not dependent on distance traveled.

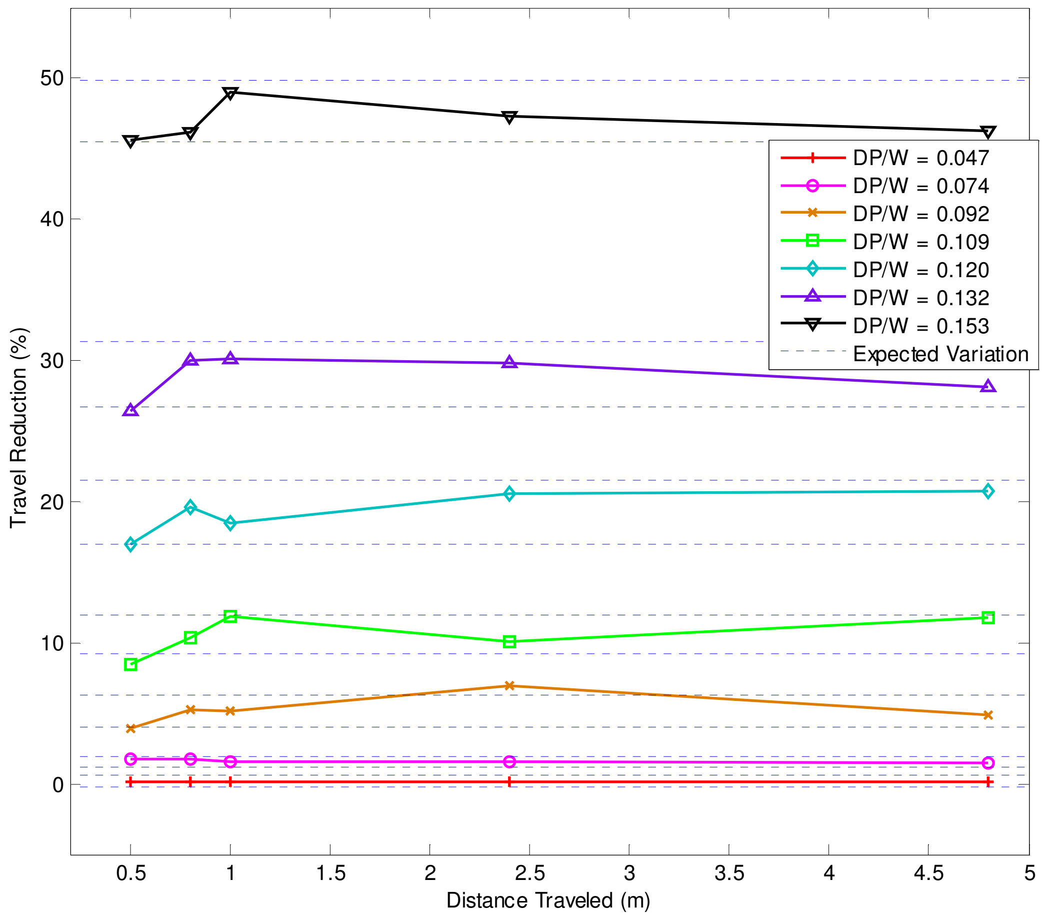


Figure 52. The variation of *TR* with distance traveled for selected, constant *DP* forces, and the expected variability of *TR* for each *DP*.

The recommendations based on the results of this study follow. Ff time is an issue, the ramped-*DP* test technique will not produce significantly different results and is the most time efficient, as a large amount of *DP* forces can be tested to measure corresponding *TR*. However, it is recommended to use a small distance, stepped-*DP* technique as it is less sensitive to error as the *TR* is calculated over a larger increment, which reduces the effect of short-lived changes in performance due to variations in soil conditions, vehicle dynamics, and measurement error.

6.5 Effects of Variations in Terrain Preparation Density on Performance

As a revision of the study conducted in Section 5.4, developing general relationships between the terrain preparation density of a soil, as measured by *G*, and vehicle performance is useful for designing terrain conditions that will decrease the variability of vehicle performance due to variations in density both during and between tests. The incentive for this study began with findings in Section 5.1, that the vehicle performance in the T3 and T2 terrain conditions was similar. Because the T3 condition took less time to prepare, it was useful in increasing the economic efficiency of conducting *DP* testing at GRC. However, more concrete evidence was needed to conclude that the T3 and T2 terrain conditions did consistently produce the same performance results. While the study in Section 5.4 was inconclusive because the *DP* force could not be controlled, the same motivation existed: to design terrain conditions for GRC-1 where vehicle performance was insensitive to variations in relative density. However, the methodology of how to conduct the experiments was revised to eliminate sources of error of the previous procedure, and to make the experiments more efficient by gaining more useful information for the quantity of experiments conducted. Also, the analysis of the data was revised to draw more insightful conclusions. In this chapter, the preparation of the terrains and test procedure are described, followed by a discussion of results and recommendations.

6.5.1 Description of Terrain Preparation and Test Procedure

The terrain conditions developed in Section 5.4 were reevaluated to ensure that each preparation would consistently produce the terrain density, as measured by *G*, in the desired regions. This was found to be true. Also, it was of interest to add an additional region, called Region 0, which is less dense than the T3 condition, to evaluate performance for a looser condition than T3. This region was added as it was noted that sometimes the T3 preparation procedure resulted in a looser condition than desired, and while compaction was not in the T3 preparation procedure, the entire terrain would normally have to be re-prepared. These terrain conditions used in this study are defined in Table 7. In coordination to the terrain condition procedures described in Section 5.4, for the loosest conditions, the soil was only shoveled, raked, and leveled according to the T3 terrain preparation procedure in Section 3.5.2.1. Additional compaction was obtained using a 10-inch square tamper with the drop height and number of passes listed in Table 8. The terrain conditions were measured by sixteen cone penetrometer insertions and the statistical verification procedure described in Section 3.5.2.4.

Table 7. The terrain conditions used to develop general relationships between relative density, as measured by *G*, and performance [4].

Terrain Condition	Range of, *G* (kPa/mm)	Measured Mean, *G* (kPa/mm)	Mean Bulk Density, ρ (g/cc)	Mean Relative Density, D_R
R0	< 2.0	1.86	1.61	2 %
R1	2.25 ± 0.25	2.10	1.62	6 %
R2	2.75 ± 0.25	2.70	1.64	13 %
R3	3.25 ± 0.25	3.31	1.65	20 %
R4	3.75 ± 0.25	3.78	1.67	26 %
R5	4.25 ± 0.25	4.40	1.69	34 %
R6	> 4.5	5.13	1.71	42 %

Table 8. Tamper drop height and number of passes to obtain the desired GRC-1 terrain conditions.

Terrain Condition	Tamper Drop Height (cm)	Number of Passes
R0	no tamping	-
R1	no tamping	-
R2	3-5	1
R3	5-8	2
R4	5-8	3
R5	5-8	5
R6	5-8	7

The test vehicle for all tests was Scarab under a 100 kg wheel load and equipped with the treadless pneumatic tires inflated to 30 psi. This vehicle setup was selected to increase contact pressure and achieve high sinkage in order to increase the effects of the soil on the performance of the vehicle.

The original test procedure described in Section 5.4 was revised to obtain more useful information for the amount of experiments that were conducted. As the 0.5 m test technique was found in Section 6.4 to no produce significantly different results than any of the other distance traveled techniques, it was selected to conduct this study. In addition, instead of preparing three terrain conditions per experiment, only one terrain condition was prepared for the entire bin length, and an entire *TR-DP* curve was obtained for that terrain condition. This method would reduce the possibility of error due to varying terrain density in on experiment. In summary, a single 0.5 m test was conducted to generate an entire *TR-DP* curve for each terrain condition. The implementation of the *DP* control system allows for the selected *DP* forces to be replicated for each test. Again, it is important to note that when using the 0.5 m technique, only the data from the last 0.3 m of vehicle travel for each constant *DP* force was used to calculate *TR*.

6.5.2 Results and Recommendations

As this test was novel, little information could be used to base a hypothesis, and intuition was used to formulate the hypothesis as *TR* should decrease with increasing density. But existing experiments in Section 5.1 revealed that the *TR* does not significantly differ as the density of the terrain increases from the T3 to T2 condition. While this was taken into consideration, it was more practical to prove that performance in T3 did differ from T2, instead of trying to prove that performance would remain unchanged. Thus, the hypothesis was that the *TR* would decrease increasing density of the terrain preparation (decrease from R0 to R6).

However, the magnitude of the quantity by which the *TR* would decrease, and the rate of decrease, was uncertain.

The *TR-DP* curves for each of the seven terrain preparations, as defined in Table 7, are shown in Figure 53. As expected, the *TR* of the vehicle generally decreases with increasing *G,* and in turn the density, of the terrain preparation increases. This is shown in Figure 53 by the separation of the *TR-DP* curves, where more dense terrains produce less *TR* for each *DP*, and the curves shift down and to the right. It can be noted here again that the terrain conditions, *G* = 1.86, 2.21, and 2.69 kPa/mm, seem to produce the same *TR-DP* curves. In more dense terrains, *G* >2.69 kPa/mm, the *TR-DP* curves follow the hypothesized trend.

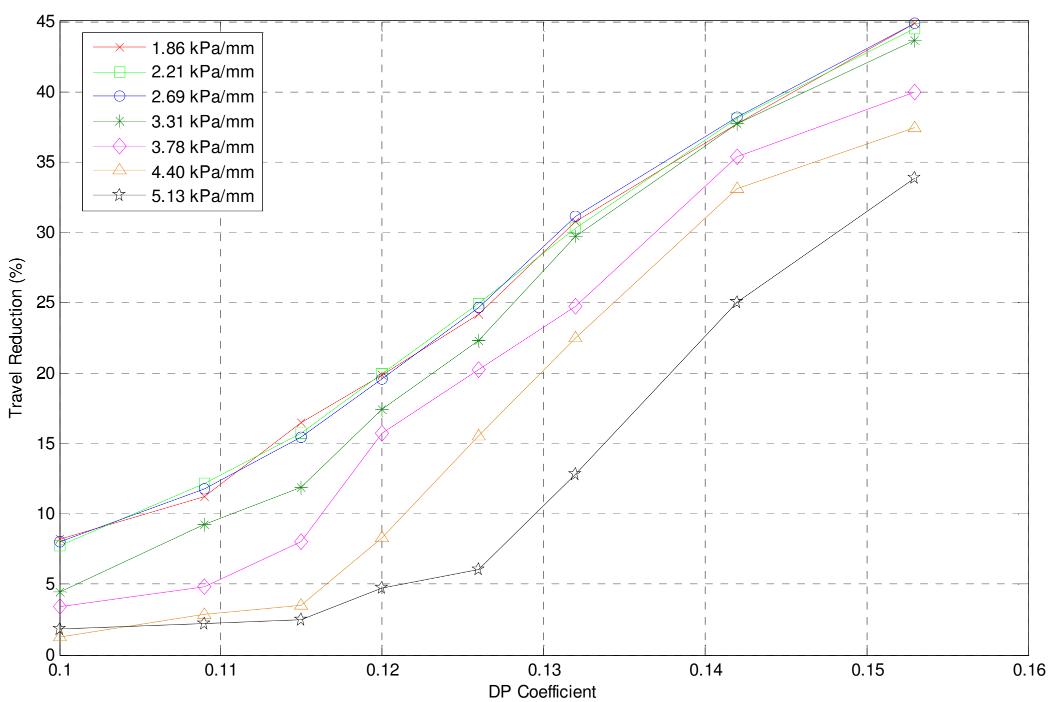


Figure 53. The *TR-DP* relations while operating in the seven different terrain conditions [6].

A better representation of the data shown in Figure 53 is shown in Figure 54 as a plot of the *TR* vs. *G*, for the different *DP* forces. Again, the expected trend of *TR* decreasing with increasing *G* is evident, but the magnitude and shape of the trends are visible. For each constant *DP*, the *TR* is relatively constant to region of *G* somewhere between 2.70 and 3.30 kPa/mm, and then significantly decreases on the order of approximately -5 (% / kPa/mm). It is also evident that for low *DP* coefficient (< 11.5 %) the *TR* is relatively constant for a value of *G* above 4.40 kPa/mm. The region that is most sensitive is a value of *G* between 3.30 and 4.40 kPa/mm.

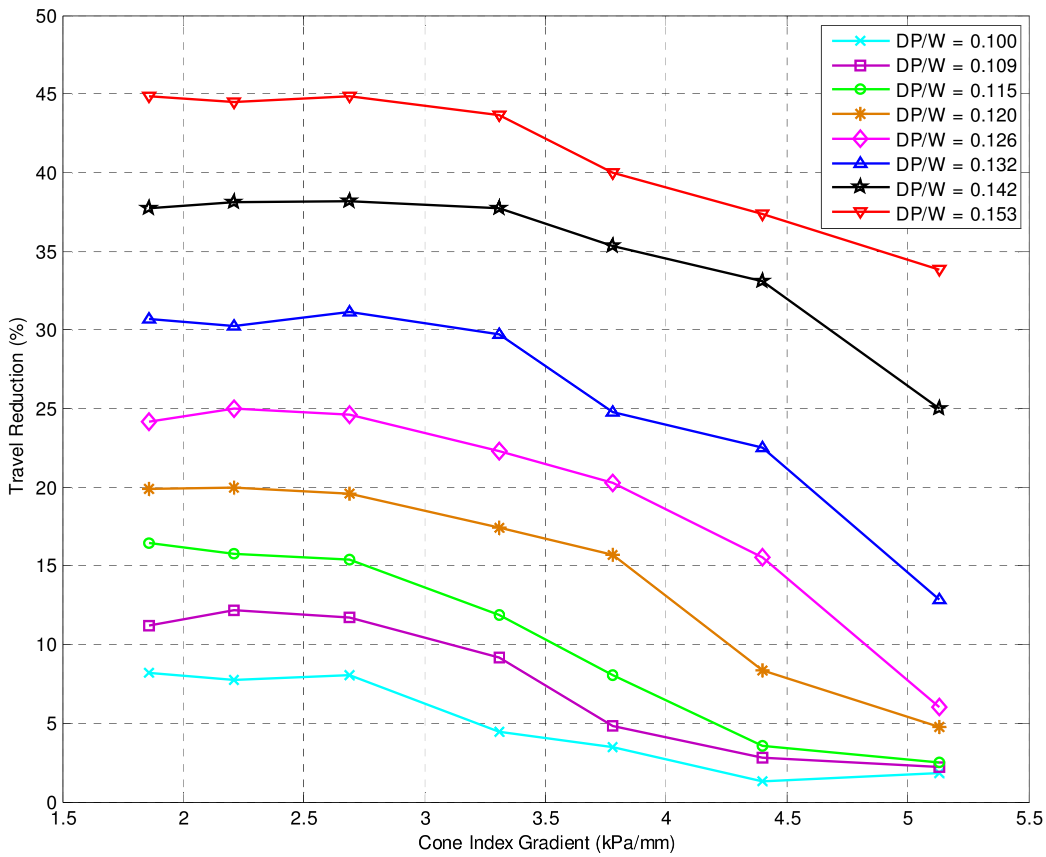


Figure 54. The *TR*-*G* relations for various, constant *DP* forces.

These results are very useful for addressing a few important questions regarding the effects of the density of the GRC-1 soil on performance. Firstly, the original motivation for this study was to deduce why the performance in the T3 and T2 terrain conditions were similar. The T3 terrain condition (2.50 ± 0.5 kPa/mm) and the T2 terrain condition (3.50 ± 0.5 kPa/mm) both, by definition, could be prepared within the least sensitive region of $G < 3.30$ kPa/mm. Hence, if the T2 condition was prepared with a density in the region of (3.00 kPa/mm $\leq G \leq 3.30$ kPa/mm) the performance in the T3 condition would not differ from the looser preparation of the T2 condition. A denser preparation of the T2 condition ($G \geq 3.30$ kPa/mm) could be significantly different. Secondly, the value of using cone penetrometer measurements to establish general trends in performance was sufficient, as very distinct performance differences were observed that were solely based on the measurements of the cone penetrometer. Lastly, significant differences in performance were observed using the mean value of G to describe the condition of the terrain, based on 8 to 16 pretest cone penetrometer measurements; further evidence that the cone penetrometer is a useful tool to measure the condition of the soil, even though surface effects are not measured or taken into consideration.

Based on the results of this study, the T3 terrain condition should be used to conduct *DP* testing in the GRC-1 soil. The T3 condition is defined within the region where performance is insensitive to variations of terrain preparation density, and variations in the performance can effectively be minimized in the T3 condition. Also, the T3 condition is the loosest of the terrain conditions and will cause high *TR*. Hence, when evaluating the safety of a vehicle operating in the lunar terrain, the T3 condition simulates essentially the "worst case" scenario. If testing is necessary in any other region of GRC-1 density, the trends in Figure 54 should be considered. Finally, as a general recommendation for conducting *DP* tests in dry, cohesionless, granular soils, terrain conditions should be developed based on the sensitivity of the performance to variations in terrain density, and not defined based on preparation method.

7. Conclusions, Recommendations, and Suggestions for Future Work

A drawbar pull test procedure was developed at NASA Glenn Research Center to study and compare the performance of light, off-road vehicles. Many test procedures and techniques have been used since the 1950's and, in turn, have made the comparison and replication of experiments difficult. Hence, the test methodology described in this report was designed at GRC with the goal of standardization to facilitate future research collaborations and expedite the development of off-road vehicles, especially exploration vehicles and wheels.

An integral part of developing such a methodology was to determine the effects of the variation of test parameters on vehicle performance. In turn, a methodology was developed to conduct variation of test parameters studies with the goals of identifying how certain test parameters affect performance and how to minimize and account for their effects before conducting a test and when analyzing the results. The specific parameters selected and tested in this thesis were the effects of variations of the starting terrain condition, distance traveled for a constant *DP*, and terrain preparation density, on performance. Upon the completion of these studies, the thesis statement was validated. Certain test parameters do have a significant impact on performance, and the effects can be distinguished from the expected variability associated with the test. This significant variability can mask the results and lead to false conclusions.

This concluding chapter will review the *DP* test procedure and conventions that were used for both a typical *DP* test and which served as a basis for the variation of parameters studies. A review of the variation of parameters studies and the main conclusions and recommendations will follow. Next, the main research contributions will be revisited, alluding to sections in the thesis. Finally, suggestions for future work will be presented.

7.1 Summary of the Drawbar Pull Test Procedure and Test Conventions Used in the Studies

The *DP* test procedure developed at NASA GRC was a constant-DP, full vehicle test. The zero condition used to measure the rolling radius was selected as a self-propelled condition traveling on a non-slip, nonyielding surface. The rolling radius used at GRC was termed the hard ground rolling radius, r_h. This zero condition was selected because a non-slip, nonyielding surface limits was a repeatable method of calculating the rolling radius that would be replicable at other research facilities.

Three, replicable terrain conditions for the GRC-1 lunar soil simulant (T3, T2, T1), and corresponding preparation procedures, were used and investigated for conducting *DP* tests. The density and consistency of the prepared terrain was measured using a cone penetrometer. The metrics utilized to define the density and consistency of the terrain was the mean and standard deviation of the cone index gradient, G, and the linearity coefficient, α.

A test was conducted using a drawbar pull rig (DPR), which applies a current-controlled force via a cable, to a hitch attached to the rear of the test vehicle, which acts as the *DP*. The vehicle was driven forward with a slow and constant wheel speed. For each *DP* force, the wheel torque, wheel rotations, and distance traveled were measured.

The metrics selected for describing the performance of a vehicle were the *TR-DP* and *PN-DP* relations. The *TR-DP* relation was selected as a metric for evaluating and comparing test techniques, because the *TR* describes the interactions between the vehicle and the terrain, and was used in the variation of parameters studies. On the contrary, the *PN-DP* relation was selected for comparing the designs of vehicle and wheels, because it relates the energy consumed to the *DP*. This is especially useful for comparing exploration vehicles as power efficiency is critical to the safety and longevity of a mission.

A statistical procedure was developed to measure the repeatability and expected variations in performance for a specific combination of test technique and terrain condition. The sample size was five repeat tests. The repeatability was measured by the standard deviation of *TR* for a single test, and the mean and maximum ensemble for the five repeat tests. The expected variability of a test technique was represented by range bars, which represents the scatter of the five identical tests for each *DP* force. The range bars were used to compare if a test was significantly different from another.

7.2 Summary of the Variation of Drawbar Pull Test Parameters Studies, Main Conclusions, and Recommendations

The test parameters selected for the variation of test parameters studies were the starting terrain condition, the distance traveled for a constant *DP*, and terrain preparation density. A summary of the main conclusions and recommendations are discussed in this section.

The starting terrain condition study was conducted to evaluate if the variations of the starting terrain among tests would affect the resultant performance. The study involved conducting an identical test on four different starting conditions: a nonyielding surface, burying the wheels, a trafficked dense terrain, and a prepared terrain. The result from this study was that the resultant performance of the vehicle was not affected by the starting terrain condition. Based on this result, the recommendation was that additional time should not be devoted to preparing the starting terrain for a test in the GRC-1 soil. In coordination with this conclusion for vehicle testing and the conclusions in [7] for single wheel testing, a general conclusion for conducting

DP tests is that the starting terrain conditions will not influence the resultant performance of the test.

The purpose of the varying the distance traveled by the vehicle at a constant *DP* was to determine if the performance of the vehicle would vary based on the variation of distance traveled. The goals were to indentify if a steady-state region of performance existed and the minimum travel distance that could be sacrificing the quality of the results. The travel distance was conducted using three test techniques: ramped-*DP*, stepped-*DP*, and constant-*DP*. The ramped-*DP* technique was conducted by linearly increasing the *DP* with travel distance; the *DP* was never constant. The stepped-*DP* technique was defined as the vehicle traveling a specified distance at a constant *DP,* and then increasing the *DP* to a new constant magnitude. The stepped-*DP* distances were 0.5 m, 0.8 m, 1.0 m, and 2.4 m. The constant-*DP* technique was driving the test vehicle the entire length of the soil bin (4.8 m) at one, constant *DP*. The results from this study were that no steady-state region of performance was evident, and there were no significant differences in performance at the different travel distances.

Based on these conclusions, if time efficiency is important, the ramped-*DP* technique can be used successfully. The stepped-DP technique for a distance less than or equal to 0.8 m will be used at GRC. This technique was selected primarily because specific *DP* forces can be tested and more easily repeated, and a larger sample of data can be acquired for a specific *DP*, as compared to the ramped-*DP* technique.

The goal of varying the density of the prepared terrain, as measured by *G*, was to develop relationships regarding how performance would vary with the terrain preparation of the GRC-1 soil. This study was conducted by developing terrain conditions that divided the range of GRC-1 densities of interest ($2.0 < G$ (kPa/mm) < 5.5) into equal regions. Seven, repeatable terrain conditions and procedures were developed, and the entire soil bin was prepared for each terrain condition. An identical test was conducted in each terrain. The relationships found were that for $G < 3.30$ kPa/mm, the *TR* was insensitive to changes in density. Beyond this region, the *TR* decreased with *G* at a rate of approximately -5 (% / kPa/mm).

The terrain conditions for GRC-1were developed based on the preparation method and the range of *G* that resulted. Based on the results, it is strongly recommended to never define terrain conditions in this way. Instead, the relationships between performance and the terrain measurement metric(s) should be experimentally determined, and the terrain conditions should be defined based on these relationships. For instance, the T2 terrain condition was defined as $G = 3.5 \pm 0.5$ kPa/mm; hence, based on the aforementioned trend, performance in a loose T2 preparation will significantly differ from a more dense T2 preparation, outside the expected variability. Since the T3 terrain condition falls completely within the region of insensitivity, it will be used henceforth for *DP* tests at GRC.

7.3 Main Research Contributions

The main research contributions of the author are stated subsequently:

1) Perform an analysis of previous studies to aid in the development of the test methodology at NASA GRC (Chapter 2):
    a. Identify *DP* methodologies that have been developed, including testing and soil preparation, techniques, procedures, and metrics
    b. Analyze variation of test parameter studies that provide insightful information to aid in the identification of important parameters and to develop the methodology to conduct the studies in this thesis
2) Collaborated in the development of the *DP* test methodology at NASA GRC (Chapter 4)

3) Identified the importance of studying the effects of the variation of test parameters and formulated a working hypothesis (Chapters 5,6)
4) Development of the methodology experimentally analyze the effects of the variation of test parameters on the performance of a vehicle (Chapters 5,6)
5) Performed the experimentation and analysis of the aforementioned studies (Chapters 5,6)
6) Provided recommendations that were implemented into the NASA GRC methodology to avoid sources of variability associated with various test parameters, how to account for the variations in the analysis of the performance results, while improving the repeatability and increasing the economic efficiency *DP* testing (Chapters 5,6)
7) Proposed generalized recommendations and provided insight regarding the value of conducting variation of test parameters studies for *DP* testing and how to develop the testing methodology, in addition to suggesting items for future work (Chapter 7)

7.4 Suggestions for Future Work

Drawbar pull test methods have been continually developed since the 1950s, and many different research approaches have been taken. While considerable progress has been made in understanding how to develop a repeatable test and how to interpret and utilize the results, the variety of the methods that have been used have made comparative and repeat studies difficult. Therefore, a general recommendation is that future studies should be conducted with the goal of developing a global, standard methodology.

More specifically, in an extension of the variations of parameters studies in this report, future studies should be conducted to identify other influential test parameters and to characterize and model relationships between individual test and soil parameters and performance. By understanding how individual parameters affect performance, the variability of test results can be effectively minimized beforehand and comparative studies to be more conclusive as the variability could be explained.

While the variation of parameters studies in this report were conclusive, they are specific to the GRC-1 terrain and the selection of test vehicle and wheels at the GRC facility. These studies should be repeated for a variety of dry, granular, sandy soils to develop relationships that can be generalized for these soils. Also, the studies should be conducted at a variety of loads and wheel types to ensure that the relationships found in this report are not specific to the vehicle setup. Due to time constraints, the variation of parameters studies were evaluated using a small sample size. A more robust test matrix should be tested to statistically eliminate random error.

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Apendix A

Provided in this appendix are tables containing the data displayed in the corresponding plots in Chapter 6.

Table 9. Repeat test data for the 0.5 m test technique in the T3 terrain condition.

Repeat 1		Repeat 2		Repeat 3		Repeat 4		Repeat 5	
DP/W	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***
0.047	0.073	0.047	0.931	0.047	0.250	0.047	0.551	0.047	0.215
0.060	0.468	0.060	1.337	0.060	0.632	0.060	0.948	0.060	1.256
0.074	1.352	0.074	1.782	0.074	1.040	0.074	1.784	0.074	1.553
0.083	2.342	0.083	3.199	0.083	1.415	0.083	1.616	0.083	2.228
0.092	2.993	0.092	4.486	0.092	2.185	0.092	3.141	0.092	2.668
0.100	4.356	0.101	6.109	0.100	4.106	0.101	5.170	0.100	5.913
0.109	8.910	0.109	8.646	0.109	6.154	0.109	7.524	0.109	8.601
0.115	12.651	0.115	12.174	0.115	9.618	0.115	9.830	0.115	11.565
0.120	14.556	0.120	16.420	0.120	12.090	0.120	11.954	0.120	14.596
0.126	19.038	0.126	19.983	0.126	15.890	0.126	17.161	0.126	19.396
0.132	24.927	0.132	25.418	0.132	20.745	0.132	22.860	0.132	24.276
0.142	34.156	0.142	34.623	0.142	30.550	0.142	31.122	0.142	35.342
0.153	42.128	0.153	45.177	0.153	40.831	0.153	42.385	0.153	44.882

Table 10. Data for the Starting Terrain Condition tests.

Buried		Non-yielding Surface		Dense soil		Prepared Soil	
DP/W	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***
0.046	0.004	0.046	0.135	0.046	0.126	0.046	-0.281
0.060	0.698	0.060	1.127	0.060	0.778	0.060	0.661
0.074	1.994	0.074	1.351	0.074	1.628	0.074	1.530
0.083	2.615	0.083	2.057	0.083	2.494	0.083	2.800
0.092	4.343	0.092	2.967	0.092	4.194	0.092	4.797
0.100	6.522	0.100	5.918	0.100	6.081	0.100	7.002
0.109	10.351	0.109	10.176	0.109	11.659	0.109	10.426
0.115	13.863	0.115	14.048	0.115	13.960	0.115	15.525
0.120	17.247	0.120	16.717	0.120	18.596	0.120	18.481
0.126	21.512	0.126	23.725	0.126	24.294	0.126	22.121
0.132	26.296	0.132	29.075	0.132	28.141	0.132	26.684
0.142	36.685	0.142	35.769	0.142	38.247	0.142	37.473
0.153	45.144	0.153	45.655	0.153	47.355	0.153	46.009

Table 11. **D**ata for the Effects of Distance Traveled at Constant Drawbar Pull Force tests.

Ramped-DP		**Constant-DP (4.8 m)**	
DP/W	***TR (%)***	***DP/W***	***TR (%)***
0.047	0.147	0.047	0.196
0.060	1.575	-	-
0.074	1.210	0.074	1.441
0.083	3.113	-	-
0.092	4.742	0.092	4.833
0.101	5.633	-	-
0.109	11.063	0.109	11.802
0.115	14.190	-	-
0.120	19.110	0.120	20.702
0.126	21.921	-	-
0.132	29.569	0.132	28.140
0.143	39.793	-	-
0.154	47.662	0.153	46.231

Stepped-DP							
0.5 m		**0.8 m**		**1.0 m**		**2.4 m**	
DP/W	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***
0.047	0.169	0.047	0.159	0.047	0.160	0.047	0.123
0.060	1.122	-	-	-	-	-	-
0.074	1.757	0.074	1.777	0.074	1.564	0.074	1.569
0.083	2.648	-	-	-	-	-	-
0.092	3.931	0.092	5.233	0.092	5.132	0.092	6.969
0.101	5.945	-	-	-	-	-	-
0.109	8.442	0.109	10.392	0.109	11.853	0.109	10.036
0.115	12.682	0.115	15.917	-	-	-	-
0.120	16.988	0.120	19.567	0.120	18.437	0.120	20.588
0.126	20.954	0.126	24.905	-	-	-	-
0.132	26.399	0.131	30.048	0.132	30.098	0.132	29.823
0.142	36.088	-	-	-	-	-	-
0.153	45.642	0.153	46.183	0.153	49.002	0.153	47.271

Table 12. Data for the Effect of Variations in Terrain Preparation Density tests.

R0 G = 1.86 kPa/mm		**R1** G = 2.21 kPa/mm		**R2** G = 2.69 kPa/mm		**R3** G = 3.31 kPa/mm	
DP/W	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***
0.101	8.183	0.100	7.745	0.101	8.073	0.100	4.475
0.109	11.223	0.109	12.159	0.109	11.759	0.109	9.211
0.115	16.483	0.115	15.745	0.115	15.439	0.115	11.870
0.120	19.902	0.120	19.980	0.120	19.608	0.120	17.415
0.126	24.168	0.126	24.986	0.126	24.662	0.126	22.286
0.132	30.728	0.132	30.279	0.132	31.136	0.132	29.757
0.142	37.742	0.142	38.101	0.142	38.203	0.142	37.738
0.153	44.866	0.153	44.500	0.153	44.829	0.153	43.677

R4 G = 3.78 kPa/mm		**R5** G = 4.40 kPa/mm		**R6** G = 5.13 kPa/mm	
DP/W	***TR (%)***	***DP/W***	***TR (%)***	***DP/W***	***TR (%)***
0.100	3.461	0.101	1.315	0.100	1.844
0.109	4.818	0.109	2.831	0.109	2.224
0.115	8.034	0.115	3.547	0.115	2.535
0.120	15.708	0.120	8.353	0.120	4.775
0.126	20.281	0.126	15.546	0.126	6.024
0.132	24.780	0.132	22.518	0.132	12.826
0.142	35.356	0.142	33.123	0.142	25.029
0.153	40.017	0.153	37.400	0.153	33.853