To the Graduate Council:

I am submitting herewith a thesis written by James Robert Kane entitled “Terrain Impacts from Vehicle Operations Across Multiple Passes.” I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Biosystems Engineering Technology.

Paul Ayers, Major Professor

We have read this thesis
and recommend its acceptance

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(Original signatures are on file with official student records.)

Terrain Impacts from Vehicle Operations across Multiple Passes

A Thesis Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

James Robert Kane

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ABSTRACT OF THESIS

Terrain Impacts from Vehicle Operations across Multiple Passes

This study, conducted on August 12th and 13th, 2008 at Fort Riley, Kansas on a clay loam soil, evaluated the terrain impacts of four commonly used tracked and wheeled military vehicles: the M1A1 Abrams Main Battle Tank, M998 High Mobility Multipurpose Wheeled Vehicle, M985 Heavy Expanded Mobility Tactical Truck, and M113 Armored Personnel Carrier. Disturbed width and impact severity were assessed along 14 spirals subjected to a maximum of eight consecutive passes for a total of 696 impact points. Understanding multipass vehicle dynamics will allow base land managers to determine with high accuracy the extent and severity of vehicle terrain impacts on military training areas, and quickly evaluate vehicle environmental impacts when used in conjunction with a GPS-based vehicle tracking system (VTS).

The goals of this project were to evaluate the impacts on vegetation by tracked and wheeled military vehicles across multiple passes in order to develop coefficients allowing more accurate predictive modeling of vehicle impacts. It was hypothesized that 1) multiple passes by tracked and wheeled military vehicles would increase vegetative and terrain impacts, 2) tracked vehicle impacts would have a higher multipass coefficient than wheeled vehicles, and 3) multipass coefficients would increase with an increase in vehicle weight and the sharpness (or severity) of turns.

Data indicate that multiple passes produce increased vegetative impacts, with multipass coefficients ranging from 0.98 to 4.44 (compared to the commonly accepted value of 2.00) depending on vehicle type and turn severity. The widely-used MPC of 2.00 fits the M985 HEMTT and M113 at sharp turns, with an MPC of 1.00 fitting the straight and intermediate turning conditions of these vehicles, as well as all turning conditions for the M998 HMMWV. For the M1A1, a MPC of 2.00 is suitable for straight paths, a MPC of 3.00 is suitable for intermediate turns, while sharp turns can be represented by a MPC of 4.00. The data suggests that MPCs should be adjusted depending on the vehicle type and according to the turning radius of the vehicle, as tracked vehicles were found to have a higher multipass coefficient than wheeled vehicles, with multipass coefficients increasing with vehicle weight and the sharpness of turns.

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CHAPTER I: INTRODUCTION

As a result of the 1969 National Environmental Policy Act (NEPA), the US Army began to take steps to assess, limit, and repair any damage done to lands by training activities. Since the early 1990's, this has culminated in the establishment of two programs designed to address the concerns of land degradation: the Environmental Security Technology Certification Program (ESTCP) and Integrated Training Area Management (ITAM). The ESTCP program's goals are to identify, demonstrate, and transfer technologies that improve efficiency, reduce liability, and save money- in this case technologies which aid land management. Better assessments and estimates of the impacts of military vehicles, particularly the dynamic properties of vehicles in motion and their terrain impacts, will allow the military to meet its goals of monitoring and managing one of the most serious sources of land degradation caused by training activities: off-road vehicle impacts. ITAM is a land monitoring and management program mandated for all Department of Defense (DOD) installations. Its purpose is to provide a realistic landscape (as close to actual battlefield conditions as possible) and to ensure training capability by balancing the usage, condition, level of maintenance, and impact on military lands.

Vehicle impacts on the environment are well-established, including but not limited to vegetation removal, increased erosion rates, soil compaction, and reduction of soil productivity (Haugen et al., 2002). Once disturbed, sensitive environments such as deserts and taiga soils might take centuries to recover or may never return to their original states (Lovich and

Bainbridge (1999). Military training activities have extensive impacts on land including direct destruction of training areas with live rounds (Li et al., 2007b), the impacts of vehicle travel on the land (Hirst et al., 2003), and less obvious impacts such as the displacement of native vegetation by introduced species (Haugen et al., 2003), and changing the plant species composition of areas as identified by Li et al. (2007a). The US Army is responsible for maintaining about 5 million hectares of land across its installations (Haugen et al., 2002). This study used an established measure of vegetative terrain impacts, the vehicle cumulative impact width (CIW), to explore to what degree multiple vehicle passes increase impacts on the terrain.

CHAPTER II: LITERATURE REVIEW

Integrating vehicle impact study results into vehicle based impact models is needed in order to predict vehicle impacts based on vehicle dynamic properties, site data, and data from previous impact studies. At this time, there is a solid foundation in terms of field study methodology and previously collected vehicle data for a variety of vehicle impact types and a variety of vehicle types and installation locations. Previous studies have examined the relationship between vehicle impacts and their relationship to vehicle dynamic properties. Historically, this has been done using replicated plot field studies which assess vegetative and terrain impacts over single and multiple passes and straight and/or curved vehicle tracks.

Vehicle Tracking

Several previous studies have explored and validated the concept of using GPS-based systems to track vehicles and gather information on vehicle dynamic properties. Haugen et al. (2000) developed a three-point turning radius calculation method for determining turning radius from GPS data. This was followed by a study by Haugen et al. (2002) that detailed the development of a self-contained GPS-based tracking system designed to allow the evaluation of vehicle impacts caused by US Army training maneuvers, including an evaluation of environmental impacts at a US Army training installation. Subsequently, Affleck et al. (2004) used a GPS-based vehicle tracking system to study Army Stryker vehicles along spirals and ovals.

The same year, Ayers et al. (2004) evaluated GPS for multipass vehicle tracking, finding that GPS was able to effectively monitor a vehicle's position and dynamic properties, even though static accuracy varied from receiver to receiver tested. GPS tracking systems have been used to identify newly formed and previously unidentified roads in a US Army training area (Ayers et al., 2005). These studies have shown that GPS-based tracking systems can plot vehicle movements in the field with a high degree of accuracy and reliability, making such systems well suited for the current study of multipass vehicle dynamics.

Vehicle Rut Formation

Quantifying military vehicle impacts, and specifically the impact of vehicle rutting on terrain has been the subject of several studies. Braunack and Williams (1993) tested an M113 and a Leopard Tank on three types of terrain: artificially denuded pasture, normal pasture, and wet pasture. By subjecting each treatment to up to eight straight line multiple passes, soil disturbance increased with increased passes, with initial water content found to be a determiner of soil strength and disturbance potential. Importantly, Braunack and Williams (1993) stated that regression analysis can assist in developing models to predict soil disturbance if the soil strength and water content of soils are known.

A discussion of multipass rut depth predictive equations was assembled by Saarilahti (2003), who summarized relevant literature from 1965 to 1989 concerning multipass rut depth. By combining equations, Saarilahti (2003) introduces a general multipass equation, given as:

$$Z_n = \left(z_{n-1}a_n + z_1 a_n\right)\frac{1}{a_n}$$

Where z_n is the rut depth after the n^{th} pass in meters, z_{n-1} is the rut depth after $n-1^{th}$ passes in meters, z_1 is the estimated rut depth of the first wheel at the n^{th} pass with no prior soil disturbance, and a_n is the multipass coefficient for the n^{th} wheel pass.

Interestingly, while the literature states that a multipass coefficient (MPC) of a= 2.00 is used in many predictive equations, the MPC can vary depending on the soil type (silt, fine sand, sand, gravel) and the soil moisture content. For example, silt at 20-35% moisture has a MPC of 2.00, while gravel at 5-10% moisture has a MPC as high as 26 (Saarilahti, 2003).

Ayers (1994), Affleck et al. (2004), and Althoff and Thien (2005) each determined that decreased turning radius (sharp turns) led to increased soil disturbance and deeper track ruts as compared to straight path travel. Additionally, rut formation on curves was found to be significantly greater for the outside track as compared to the inside track of turning vehicles.

Shoop et al. (2005) examined Army LAV 25 wheeled vehicles as a surrogate for Stryker wheeled vehicles, visually comparing observed rutting by the LAV 25 to previously-developed rutting potential maps generated using the NATO reference mobility model (NRMMII) combined with land management techniques. NRMMII was used to quantify the impacts of vehicle maneuvering, relating training activities in terms of Maneuver Impact Miles (MIM), which relate

the type of vehicle and training exercise to the terrain impact, then using location or seasonally-specific Land Condition Curves to relate these MIMs to the severity of terrain impact. By using the NRMMII model and assessed vehicle impacts, this study was able to generate facility maps showing areas of high and low potential terrain impacts suitable for use by facility managers (Shoop et al., 2005). Following the generation of facility land use maps, the seasonal (winter/spring) rutting impacts of Stryker wheeled vehicles were assessed using multiple-pass ovals and spirals. Ground disturbance was related to turning radius and terrain impacts were assessed using the visual impact severity checklist developed by Haugen et al. (2000).

Multipass Vegetative Disturbance and Vehicle Impacts

Watts (1998) used tracked vehicles at Orchard Training Area in Idaho to examine vehicle vegetation and soil impacts on a desert sagebrush community. Two types of tracked vehicle impacts were studied: sharp turns (divots) and straight-line tracks. Disturbances such as tracks and especially sharp turns were found to increase the percentage of bare ground, introduce exotic and invasive species, increase soil erosion and reduce soil productivity.

A study by Hirst et al. (2003) compared the disturbance effects of a large tracked vehicle and a light and medium wheeled vehicle on chalk grassland within the UK's Salisbury Plain Training Area. Established permanent plots were disturbed either by single or multiple passes. All experimental terrain impacts with the exception of a single pass of a light wheeled vehicle caused significant terrain disturbance, and tracked vehicles, especially turning tracked vehicles were found to cause the most severe terrain impacts.

Haugen et al. (2003) determined vehicle dynamic properties as well as the amount of off-road vegetation removed for individual vehicles taking part in training operations at Yakima Training Center in Yakima, Wash. using GPS-based tracking systems. Instead of comparing terrain impacts caused by differing vehicle types, Haugen compared the terrain impacts of different types of training missions, noting which training activities produced the largest vegetative impacts.

Anderson et al. (2007) evaluated terrain impacts of a heavy tracked, medium and light wheeled military vehicle at Camp Atterbury, Ind. using GPS-based vehicle tracking systems. Vegetation damage was quantified by both the amount of vegetation lost and the total area impacted. The tracked vehicle produced more damage than the wheeled vehicles and turning was found to produce more damage than straight-line vehicle movement (Anderson et al., 2007).

Li et al. (2007a) conducted a study on wheeled vehicles. This study examined the relationships between turning radius and soil disturbed width, comparing an eight-wheeled vehicle (a LAV-25) to a four-wheeled vehicle (a M998 HMMWV) by running spiral patterns and taking 10-15 points along each spiral using a GPS-based vehicle tracking system to record vehicle position and velocity. By measuring the width of disturbance caused by vehicle tracks (the disturbed width, or DW) and assessing the severity of vegetative impacts (the impact severity, or IS) using the previously-discussed impact severity checklist developed by Haugen et al. (2000), this study quantified terrain disturbance and vegetative impacts using the derived unit, Cumulative Impact Width (CIW). CIW is the product of DW and IS, and can be understood as the

width of vehicle impact receiving 100% disturbance. This study established that the disturbed width model and impact severity model could accurately represent field test results.

Soon afterwards, Li et al. (2007b) conducted a second study focused on tracked vehicles. This study's objectives were to develop models for predicting terrain disturbed width and impact severity for tracked vehicles, and to verify the findings of these models. This study compared the impacts of a small tracked vehicle (M577A2 APC) to a large tracked vehicle (M1A1 combat tank) at Fort Riley, Kans. in October 2004, and at Yakima Training Center, Wash. (YTC). A separate field test was conducted using a M548 tracked vehicle at Camp Atterbury, Ind. in May 2003. This study also used spirals to determine vehicle terrain impacts, taking 10-20 points along a spiral and using a GPS-based vehicle tracking system to record vehicle position and velocity.

Affleck et al. (2004) assessed terrain disturbance generated by Army Stryker vehicles across one, four, eight, and 13 multiple passes and conducted spirals to determine maneuver impacts at differing turning radii. The objective of the multipass tests was to quantify terrain disturbance by convoying vehicles. Rutting severity, as well as soil and vegetation disturbance, was classified using the impact severity guidelines developed by Haugen et al. (2002) and quantified using cumulative impact width.

Summary

In summary, previous studies have developed a robust procedural framework for tracking and assessing military vehicles with GPS-based systems either in field studies or while training on installations, determining the extent and severity of impacts of different vehicle types in terms of rut formation, as well as determining vegetation disturbance and vehicle dynamic properties across a range of conditions, including multiple passes. However, past or current research has not been undertaken in several key areas of keen interest to land managers and others interested in vehicle terrain impacts. Such areas of interest include determining the change in tracked/wheeled vehicle impact as a function of vehicle turning radius, the relative impact, while turning, of different types of wheeled and tracked vehicles, associating the degree and location of vehicle impact with specific vehicle dynamic properties (velocity, turning radius) for comparison of impacts from different vehicles with different operating characteristics. Additionally, there is a need for the further refinement and field verification of vehicle impact prediction models in order to predict the terrain impacts of vehicles during training activities across multiple passes which has not been addressed by prior research.

Prior research has determined vehicle dynamic properties for a range of vehicles at a variety of training sites. This includes the Stryker wheeled vehicle in Alaskan permafrost and non-permafrost terrain, the M1A1 combat tank, M577 APC, and M548 cargo carrier on terrain in Yakima, Wash., Fort Riley, Kans. and Camp Atterbury, Ind., the LAV-25 at Fort Lewis, Wash. and the M1097 HMMWV at Yuma Proving Ground, Ariz. Despite the range of vehicle types and installations listed, no previous study has quantified multipass vehicle dynamic properties or

refined multipass prediction methodologies with specific focus on vehicle vegetative impacts. By developing empirical multipass coefficients for military vehicle vegetative disturbances, this study will lead more accurate predictions of military vehicle training impacts on training installations, leading to less downtime for training ranges and more effective training deployment of military personnel and vehicles.

Justification and Objective

Justification

This study investigates the multipass vegetative impacts of both large and small, tracked and wheeled, commonly-used military vehicles across a wide range of turning radii. By quantifying the type and severity of vehicle impacts based on the number of vehicle passes and the turning radius of the vehicle, as well as determining the cumulative impact width for the vehicle, this study will also validate previously developed models and assist in the development of a predictive approach to vehicle impacts by developing empirically-derived coefficients for multipass vegetative impacts by utilizing a GPS-based tracking system. This study is the first to develop MPCs related to vehicle CIW, and is the first to examine the relationship between turning radius, vehicle size and mobility mechanism on CIW and MPCs.

General Objective

The two goals of this project are to evaluate the terrain impacts of four commonly used tracked and wheeled military vehicles across one, two, four and eight passes along the same path at a given velocity and turning radius, and secondly to determine multipass coefficients for vehicles as a modification to the predictive CIW equation. In previous studies rut depth studies, multipass vehicle coefficients have been assigned a value of 2.00.

In order to meet the objective of evaluate the terrain impacts of vehicles across multiple passes, the relationship between the turning radius of a vehicle, cumulative impact width (a measure of vegetative disturbance, which is a product of the width of the vehicle impact in cm and the impact severity of the vehicle from 0-100%) and the number of passes of the vehicle must be determined. To do so, a field study was conducted, utilizing a previously-developed vehicle tracking system (Haugen et al., 2002), rapid assessment visual impact assessment checklist, and protocol for assessing vehicle dynamics using GPS data. This data was then analyzed to determine multipass vehicle coefficients for vehicles as a modification to the predictive CIW equation, as well as test modifications of a previously developed theoretical prediction model developed by Li et al. (2007a, b).

CHAPTER III: Procedures

Field Data Collection

This study used four Army vehicles: the M1A1 Main Battle Tank, M113 Armored Personnel Carrier (M113 APC), M998 High Mobility Multipurpose Wheeled Vehicle (M998 HMMWV), and M985 Heavy Expanded Mobility Tactical Truck (M985 HEMTT) (Table 1, Fig. 1-4). At the test site, a relatively flat, unused area was selected which was free of large obstacles and wooded areas.

Vehicle Spirals

Vehicles were driven over terrain following spiral paths, this pattern chosen due to giving the widest range of turning radii, specifically from >150 m to <30 m, in the smallest possible space, thus maximizing the number of replicate spirals possible over the most similar terrain as possible. Both left hand and right hand turn spirals were accommodated (Table 2).

Vehicle	Mobility Mechanism	Vehicle Weight (kg)	Track/Tire Width (cm)	Track Length/ Wheelbase (cm)
M1A1 Combat Tank	Tracked	57,200	63.0	460
M113 APC	Tracked	11,700	38.0	270
M985 HEMTT	Wheeled	24,900	31.0	530
M998 HMMWV	Wheeled	3,500	29.5	330

Table 1. Study Vehicle Parameters.



Figure 1. M1A1 Combat Tank.



Figure 2. M113 APC.



Figure 3. M985 HEMTT.



Figure 4. M998 HMMWV.

Table 2. Study Vehicle Spirals

Spiral Number	Vehicle Type	Number of Impact Points	Number of Passes	Average Velocity (m/s)	Turn Direction
1	M1A1	16	1, 2, 4	4.8	Right
2	M1A1	16	1, 2, 4	3.0	Right
3	M1A1	16	1, 2, 4	3.5	Right
4	M1A1	16	1, 2, 4	4.4	Right
5	M113 APC	14	1, 2, 4, 8	4.0	Left
6	M113 APC	14	1, 2, 4, 8	3.3	Left
7	M113 APC	14	1, 2, 4, 8	3.4	Left
8	M985 HEMTT	12	1, 2, 4, 8	2.9	Left
9	M985 HEMTT	12	1, 2, 4, 8	4.1	Right
10	M985 HEMTT	12	1, 2, 4, 8	2.9	Left
11	M998 HMMWV	12	1, 2, 4, 8	1.9	Left
12	M998 HMMWV	12	1, 2, 4, 8	3.0	Right
13	M998 HMMWV	12	1, 2, 4, 8	2.0	Right
14	M998 HMMWV	12	1, 2, 4, 8	2.5	Left

Vehicle Spiral Data Collection

Before testing was conducted, the vehicle was outfitted with a Trimble AgGPS 132 GPS receiver with OmniSTAR differential correction. The GPS unit was connected to an Acumen SDR data logger, with $GPGGA and $GPRMC GPS strings collected once a second. Data was stored on secure digital media for later retrieval. GPS was used to determine each vehicle's velocity and turning radius using procedures described by Haugen et al. (2002).

Once the GPS and datalogger were verified to be collecting positional information, the vehicle, manned by an Army driver, drove in either a left or right-hand spiral, determined in advance. A typical spiral began with the vehicle following a straight path, slowly transitioning to a shallow turn and then progressing into a tighter, sharper turn as the vehicle neared the center of the spiral, finally reaching the minimum turning radius of the vehicle. The driver was instructed to attempt to maintain as near-constant a speed as possible. Each spiral included the widest possible range of turning radii experienced by the vehicle during normal operating conditions.

After the first spiral performed by the vehicle, a ground crew walked the spiral, collecting data at points approximately 5 m apart, marked along the length of the spiral with surveying flags. A Trimble AgGPS 132 GPS receiver, attached to a backpack which was connected to a Compaq Pocket PC loaded with the ArcPad mapping program, were used to collect GPS coordinates and log data for each point along the spiral.

At each marked point along the spiral, the following measurements are taken:

- Vehicle impact type is classified as an imprint, scrape, or combination

- If present, the pile (vegetation which has been sheared and piled at the edge of the vehicle track) is measured for height in centimeters
- Disturbed width of the vehicle track in centimeters (both driver side and passenger side) using fold-out rulers
- Percent severity of the impact, ranging from 0 to 100%, based upon "Guidelines for assigning impact severity values" (Haugen et al., 2000)
- Soil Drop Cone, based upon "Guide to Sampling Soil Compaction Using Hand-Held Soil Penetrometers" (Jones and Kunze, 2004)
- Soil Time Domain Reflectometry using the Spectrum Technologies TDR 300 soil moisture probe

Following the logging of data from the first pass, the vehicle was run at approximately the same velocity following as closely as possible the previously defined spiral path, delineated by the surveying flags. After this second run, the ground crew again visited each of the 14-16 points along the spiral, collecting the same information as before, ignoring the impact type. The same procedure was repeated after four passes and again repeated after a final eighth pass, for a maximum total of four measurements at each impact point. Four measures at each of 16 points = 256 observations per spiral (Table 2). For the M1A1 only one, two and four passes were conducted, as total vegetation removal occurred after four passes. Additionally, in order to characterize the soil characteristics for a given spiral, several measurements were taken at the center of each spiral. These center-spiral measurements consisted of a Soil Shear Graph, Torvane (a hand-held vane shear device for rapid determination of shear strength in cohesive soils), soil cone penetrometer, and a soil sample for later analysis of soil and biomass characteristics.

Soil Parameter Data Collection Procedures

Soil moisture (gravimetric) was assessed by taking bulk soil samples at three locations from each spiral and averaging these measures for average spiral soil moisture content. Bulk samples were measured for initial wet mass and then dried in an oven at 90ºC for 18 hrs. This gave a final dry weight measure for each sample. Results were reported as dry basis gravimetric soil moisture.

Soil bulk density was assessed by taking soil samples at three locations from each spiral, and averaging these measures for average spiral soil bulk density. Each sample consisted of a shallow cylindrical core ranging from 5.1 to 9.5 cm in length, and approximately 2.70 cm in diameter. Samples were measured for initial wet mass and then dried at 90ºC for 18-24 hrs. This gave a final dry weight measure (DB) for each sample.

Root density measures were taken by obtaining a single bulk soil sample, averaging a volume of 2.8 L and 3.7 kg, taken at the center of each spiral. Samples were soaked in water for 24 hours and gently washed over a 1-mm screen to isolate roots. Root mass was then dried for 72 hrs at 50°C and a final measurement taken. Above and belowground biomass measures were taken by obtaining bulk soil samples from the center of each spiral. Belowground biomass was soaked in water for 24 hrs and gently washed over a 1-mm screen to isolate roots. The roots were then dried for 72 hrs at 50°C. Aboveground biomass was dried at 40 - 50°C for 60 hrs.

Laboratory Analysis of Field Data

In the lab, raw GPS positional data was processed through two executable programs: a merge program which took the separate GPRMC and GPGGA strings and combined them into a single string containing all unique GGA/RMC data, and a program which sorted the combined strings into move/no move data, eliminating all GPS data for times at which the vehicles were stationary. Following this, a separate executable was used to determine the turning radius, using a three-point method, of each point along each separate vehicle spiral.

The filtered GPS data, along with calculated turning radius was then imported into the Microsoft excel spreadsheet program, where the data were sorted into labeled columns, saved as a comma separated variable file, and imported into ArcMap in order to render the GPS data for manipulation and map creation (Figure 1).

Data collected in the field via the handheld ArcPad unit were imported into ArcGIS. This impact point data was subsequently merged with the imported GPS positional data using the ArcGIS merge tool, giving a final map of spiral points with associated impact information. Hand written data sheets consisting of disturbed width (DW) and impact severity (IS) data were separately entered into Microsoft Excel and analyzed.

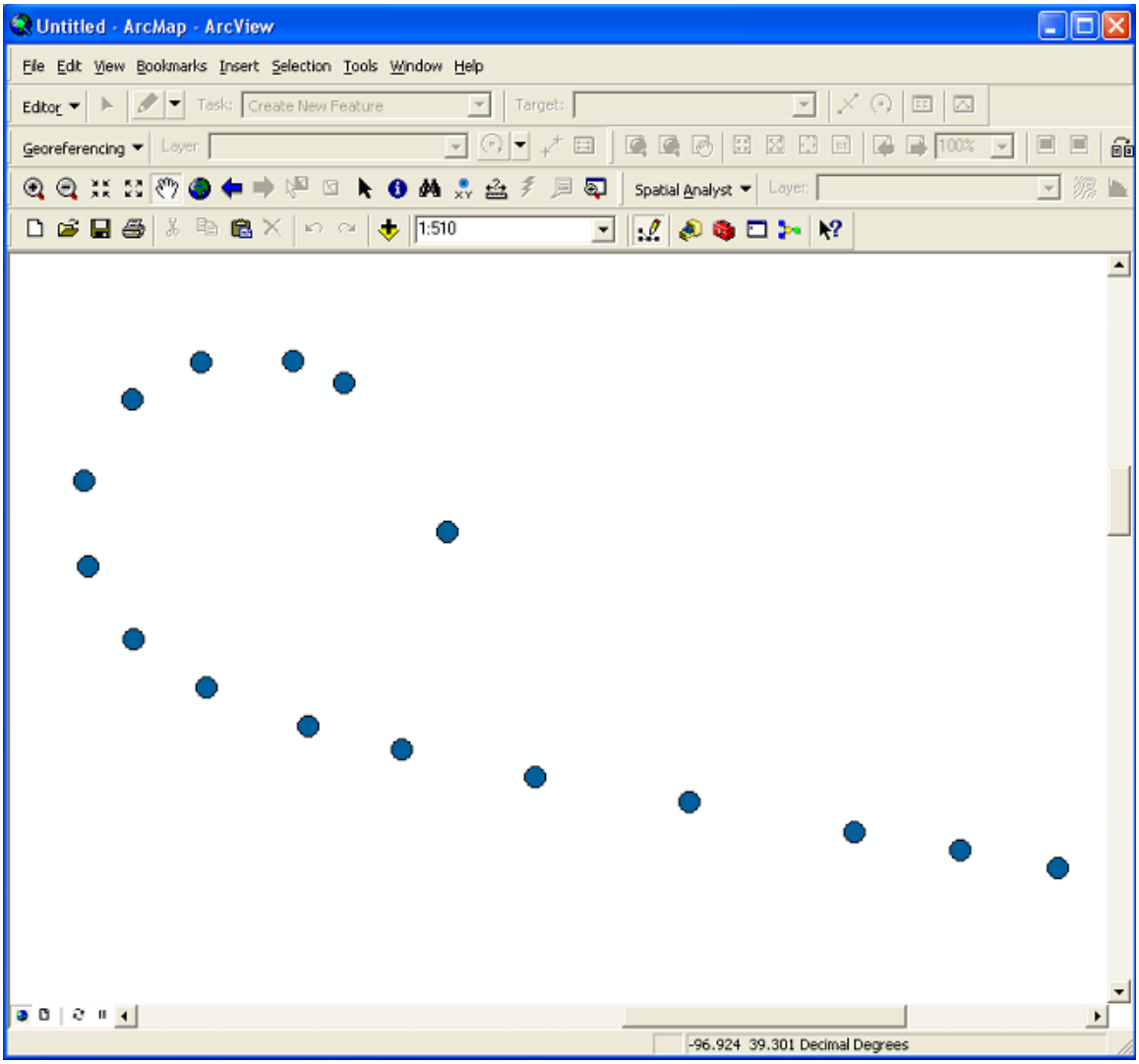


Figure 5. Vehicle Spiral in ArcGIS

Multipass Data Analysis

Multipass coefficients were determined for each vehicle for each turning condition using the following equation:

$$CIW_n = CIW_1 \times n^{\frac{1}{a}}$$

Where CIW_n is the CIW after the nth pass, CIW_1 is the CIW after the first pass, n is the number of passes, and a is the multipass coefficient.

Turning radius (TR) was determined by an executable file in the lab, with a specific turning radius associated with each vehicle spiral impact point. For each spiral, turning radii were grouped into straight, intermediate and sharp turning categories based on the following metric:

- Straight turns were classified as >80 m radius
- Intermediate turns were classified as between 30 and 80 m radius
- Sharp turns were classified as <30 m radius

TR values were averaged across all spirals for a specific vehicle to arrive at a single spiral breakdown of straight/intermediate/sharp per vehicle (Table 3). All CIW values for a specific TR across all spirals (for a specific vehicle) were averaged to calculate CIW_1, CIW for first pass.

Multipass coefficients were determined using the statistical analysis program JMP (SAS Institute Incorporated, 2010), with analyses run using nonlinear regression. The TR from all spirals for a specific vehicle are averaged to produce an idealized TR spiral (Table 3). Using the idealized TR spiral, each of the specific vehicle spirals are divided into straight, intermediate and

sharp turns. CIW_1 values are calculated for straight, intermediate and sharp turns by averaging the first pass CIW values from all vehicle spirals sharing a common turning radius. Each of the three radii has a unique value.

Once the CIW_1 value known for a specific turning radius, it is entered into the JMP formula as a multiplier to the $n^{\frac{1}{a}}$ term. All CIW values across all pass treatments for a specific TR (either straight, intermediate or sharp) are entered into JMP, with N equal to the number of passes (one, two, four or eight). For each CIW, JMP calculates a solution using nonlinear regression for the multipass coefficient parameter (MPC) b.

To determine whether true differences exist between combined vehicle MPCs (for all points and turning conditions), new MPCs were calculated using the statistical analysis program JMP (SAS Institute Incorporated, 2010), with analyses run using nonlinear regression. Inside and outside vehicle CIWs were combined into an average CIW value for each turning condition (straight, intermediate, sharp) and multipass treatment (one, two, four or eight passes). One MPC was calculated for each vehicle spiral point.

In order to determine whether or not differences existed between and within the individual spiral point MPCs calculated for each vehicle, descriptive statistics were calculated using Sound Science's Statistics Calculator (Unnasch, 2009) and unpaired t-tests were calculated using GraphPad QuickCalcs (GraphPad, 2005).

Table 3. TR Determinations (Averaged Spirals) Per Vehicle

Spiral Data Point	M1A1 Avg. TR (m)	M113 Avg. TR (m)	HEMMT Avg. TR (m)	M998 HMMWV Avg. TR (m)
1	147	150	150	150
2	143	150	150	109
3	131	150	150	85
4	124	125	90	64
5	103	42	25	48
6	67	27	23	25
7	41	24	20	23
8	28	23	19	19
9	26	23	18	16
10	25	22	15	13
11	23	20	14	12
12	22	19	13	10
13	20	17		
14	13	16		
15	9			
16	8			

CHAPTER IV: RESULTS AND DISCUSSION

Study Area Setting and Terrain Description

Fort Riley is located in northeastern Kansas, comprising approximately 41,154 ha of land within the Bluestem Prairie section of the Tall Grass Prairie biotic province (Bailey, 1976) which is characterized by grass-dominated rolling plains and stream valleys containing some wood and shrub land. Soil types include clay upland and loamy upland soils, and this area receives a mean annual precipitation of 78.7 to 119.4 cm

Fourteen spirals were run on approximately 8.1 hectares of the northwestern section of Fort Riley (Figure 6), comprised chiefly of three main soil types, all variations on silty clay loam (

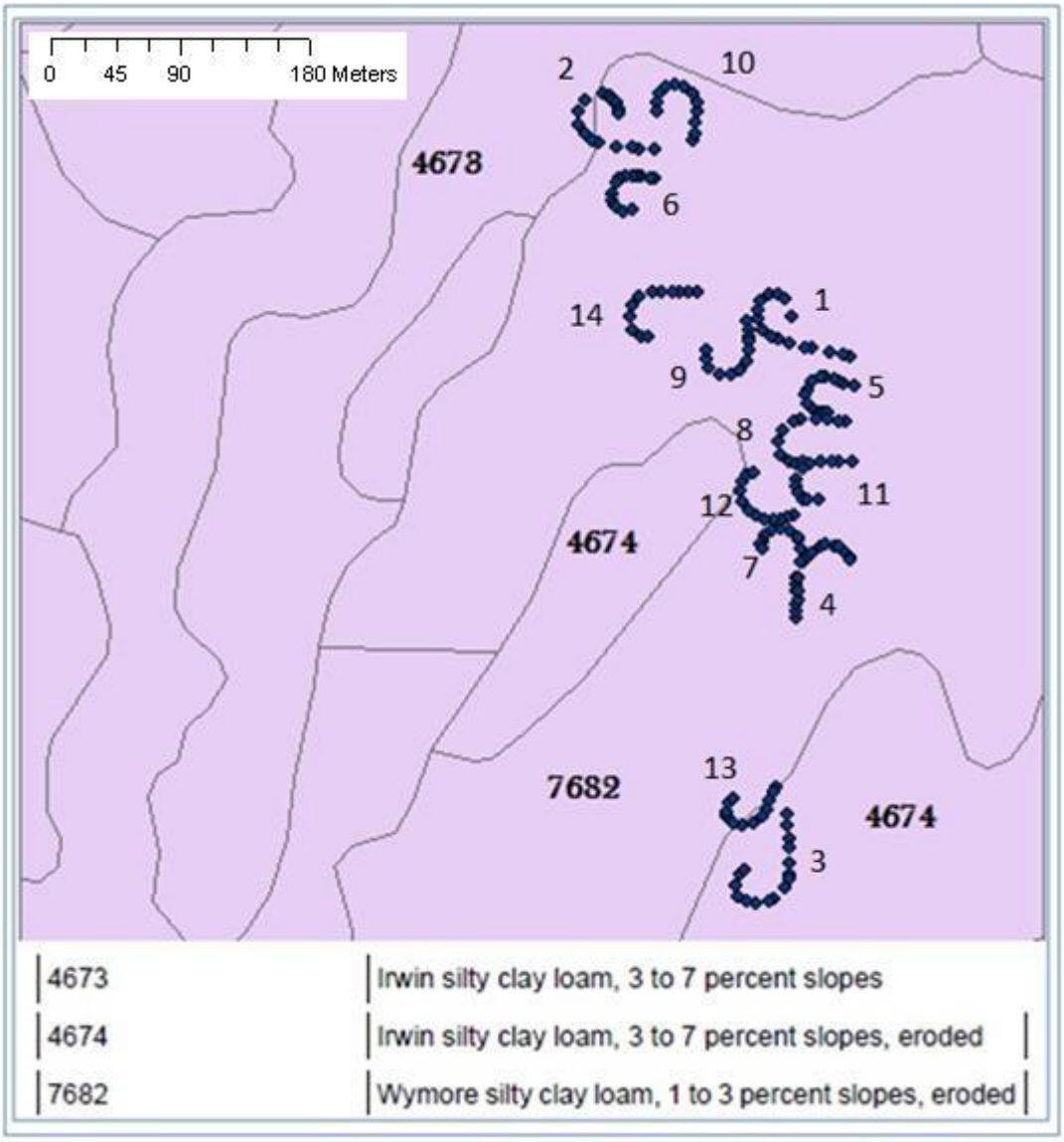


Figure 7). The vast majority of spirals were conducted on eroded Wymore silty clay loam (soil unit 7682), with spiral three and part of spiral 13 conducted on eroded Irwin silty clay loam (soil unit 4674), and a portion of spiral two conducted on uneroded Irwin silty clay loam (soil unit 4673).

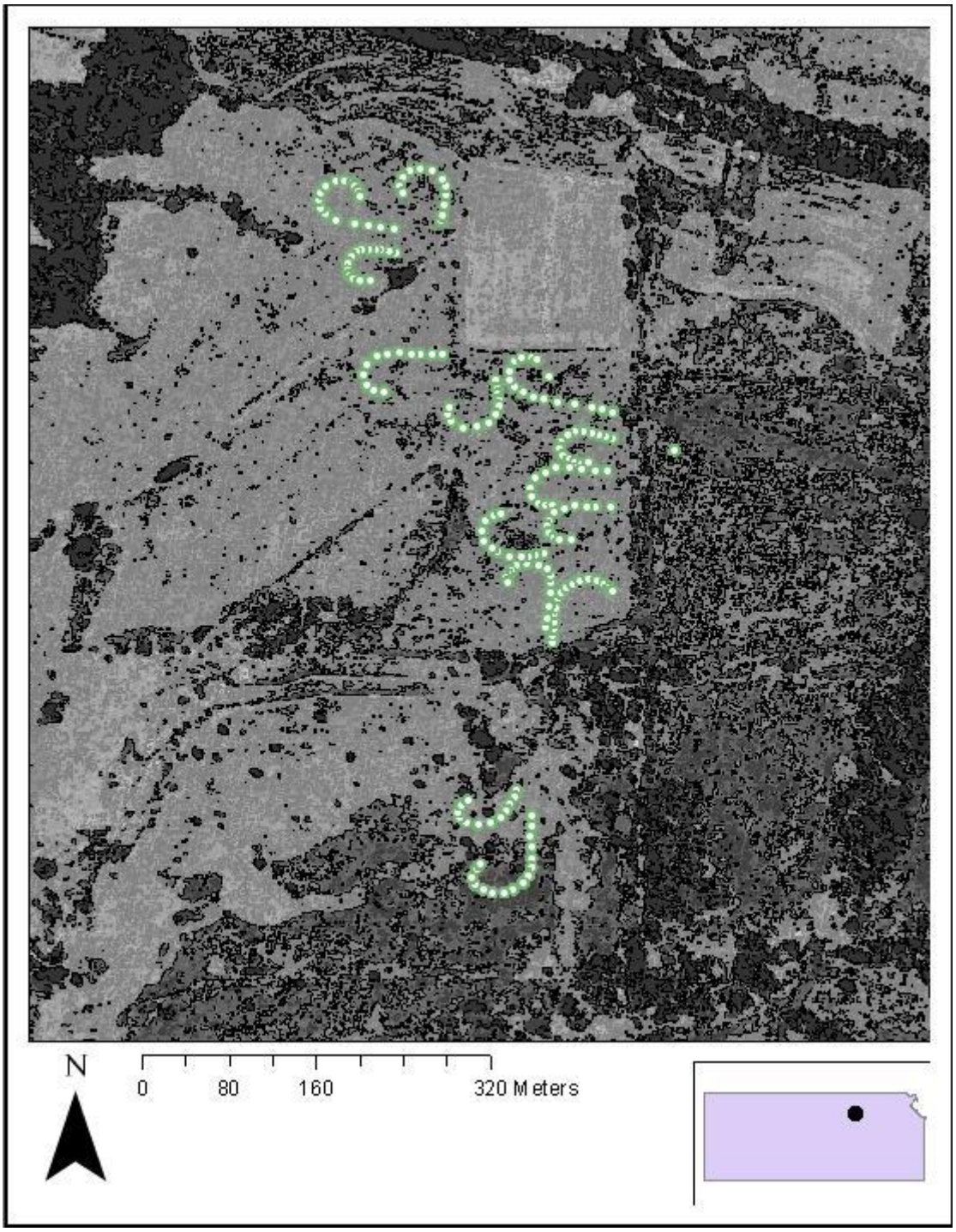


Figure 6. Fort Riley Study Area with Kansas Inset Map.

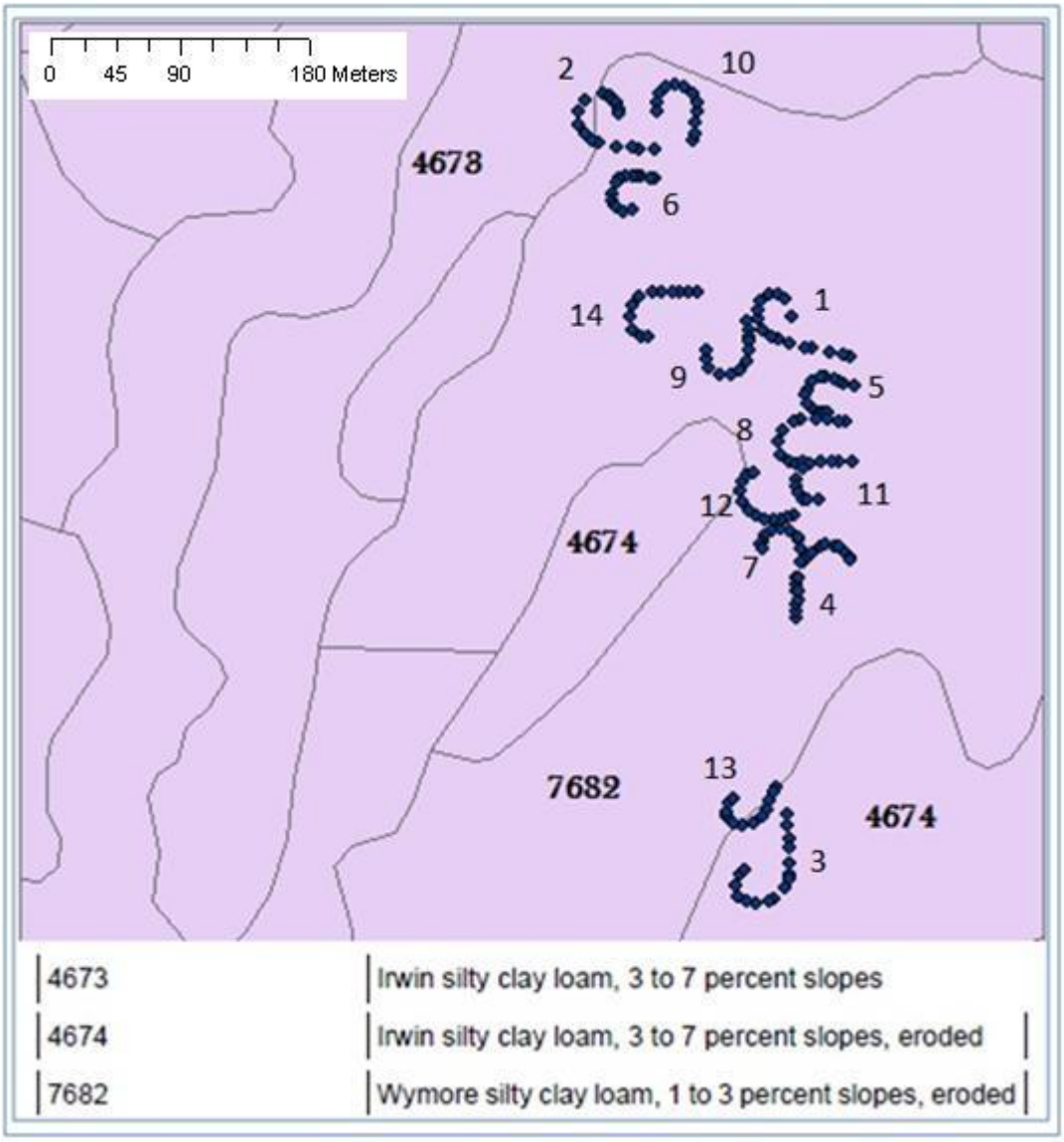


Figure 7. Vehicle Spirals Rendered on Soil Units Map.

Soil Types and Descriptions

Soil unit 4673, the Irwin silty clay loam, lies at an elevation of 304 to 469 m. It has a 3 to 7 percent slope and its parent material includes silty and clayey alluvium over clayey residuum weathered from limestone and shale.

Soil unit 4674, the eroded Irwin silty clay loam, lies at an elevation of 304 to 488 meters. It has a 4 to 8% slope and its parent material includes clayey pedisediment derived from shale.

Soil unit 7682, the eroded Wymore silty clay loam, lies at an elevation of 304 to 469 m. It has a 1 to 4% slope and its parent material includes silty and clayey loess over clayey pedisediment.

Soil Physical Properties

Moisture Gravimetric (% by Weight)

Average gravimetric moisture was 25.5% by weight (dry basis), with a high of 27.7% and low of 24.1% moisture by weight (Figure 8).

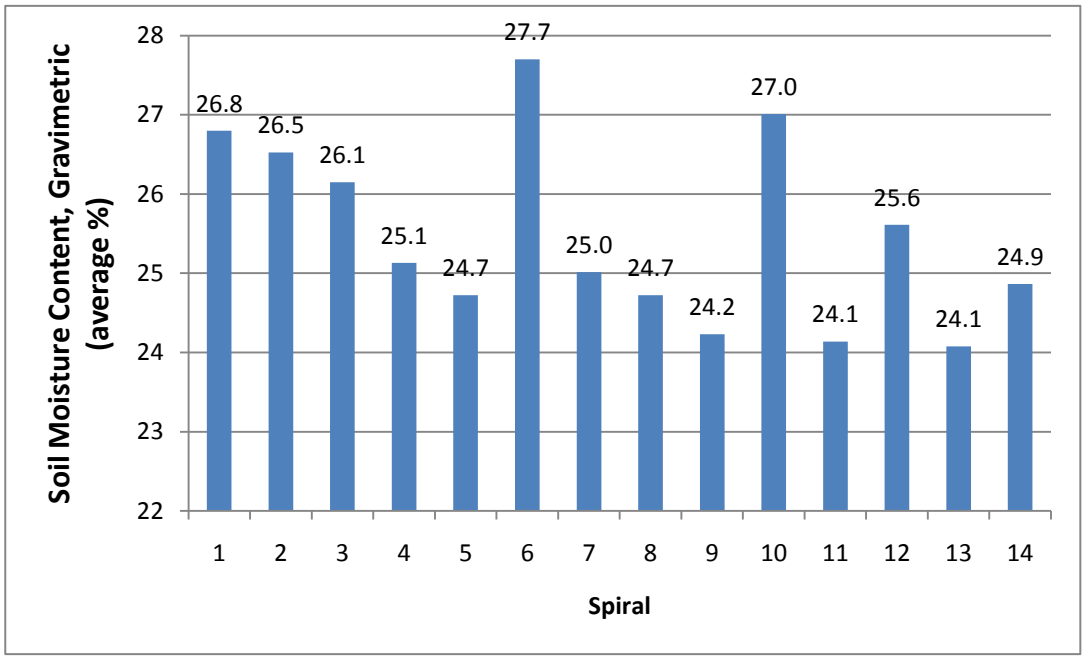


Figure 8. Gravimetric Soil Moisture by Spiral

Soil Density

Average soil density (dry basis) was 1.30 g/cm^3, with a high of 1.33 g/cm^3 and a low of 1.07 g/cm^3 (Figure 9).

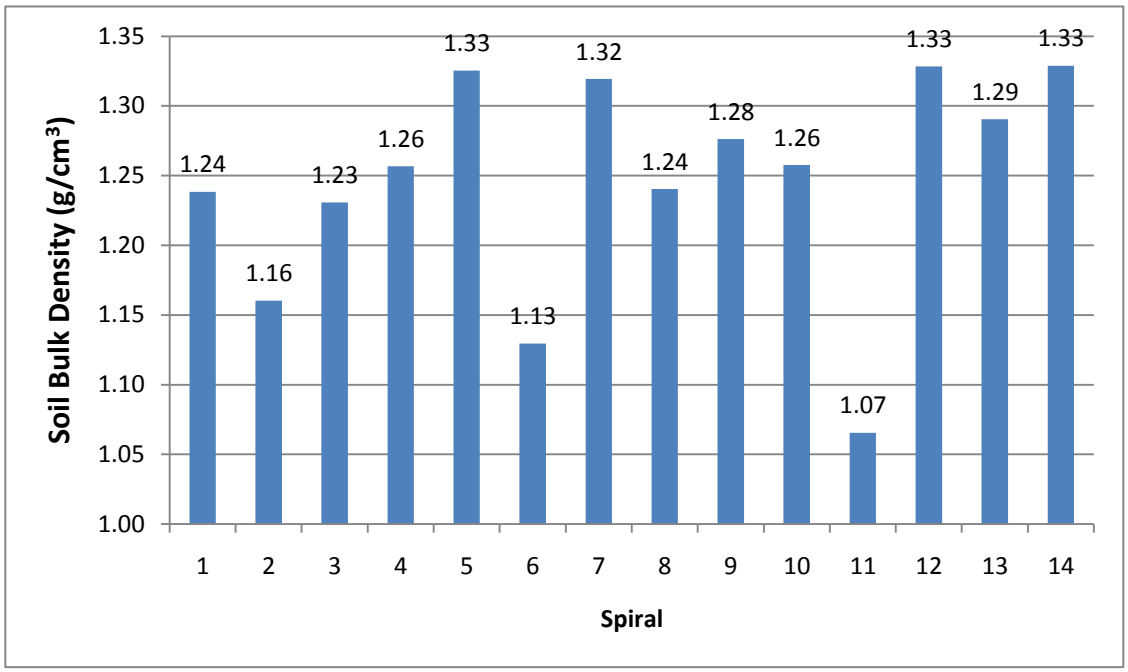


Figure 9. Soil Bulk Density by Spiral

Root Density

Average root density was 11.7 g/L, with a high of 21.2 g/L and a low of 2.20 g/L (Figure 10).

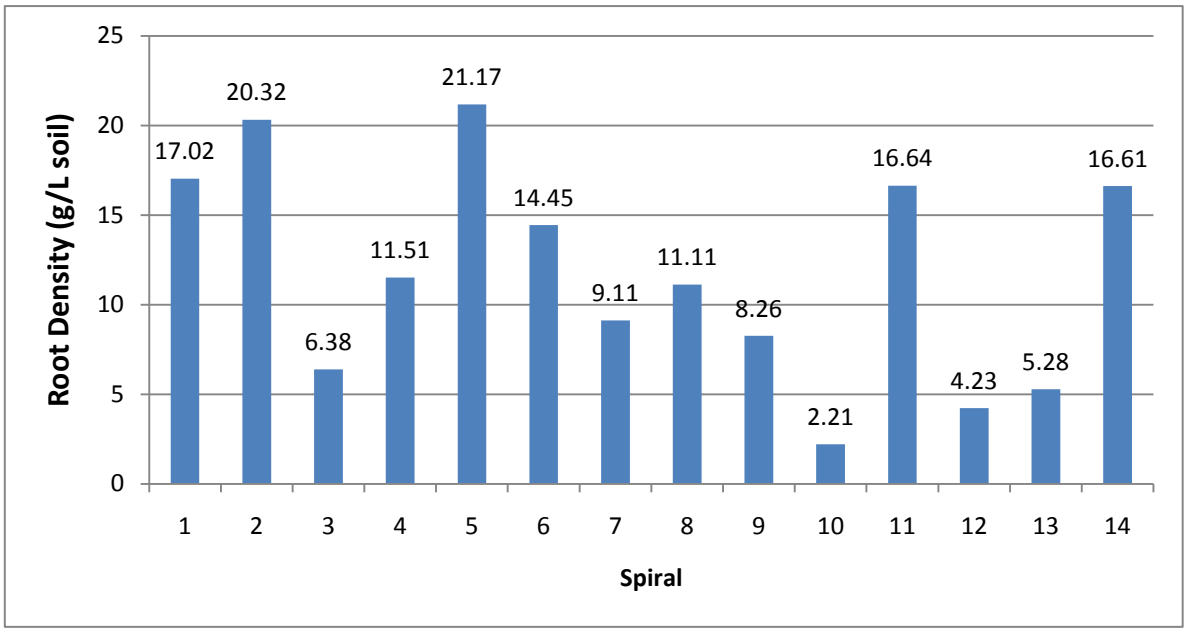


Figure 10. Root Density by Spiral

Biomass

Below ground biomass averaged 32.9 g/m^2, with a high of 62.3 g/m^2 and a low of 6.90 g/m^2 (Figure 11). Above ground biomass averaged 91.1 g/m^2, with a high of 160 g/m^2 and a low of 68.6 g/m^2 (Figure 12).

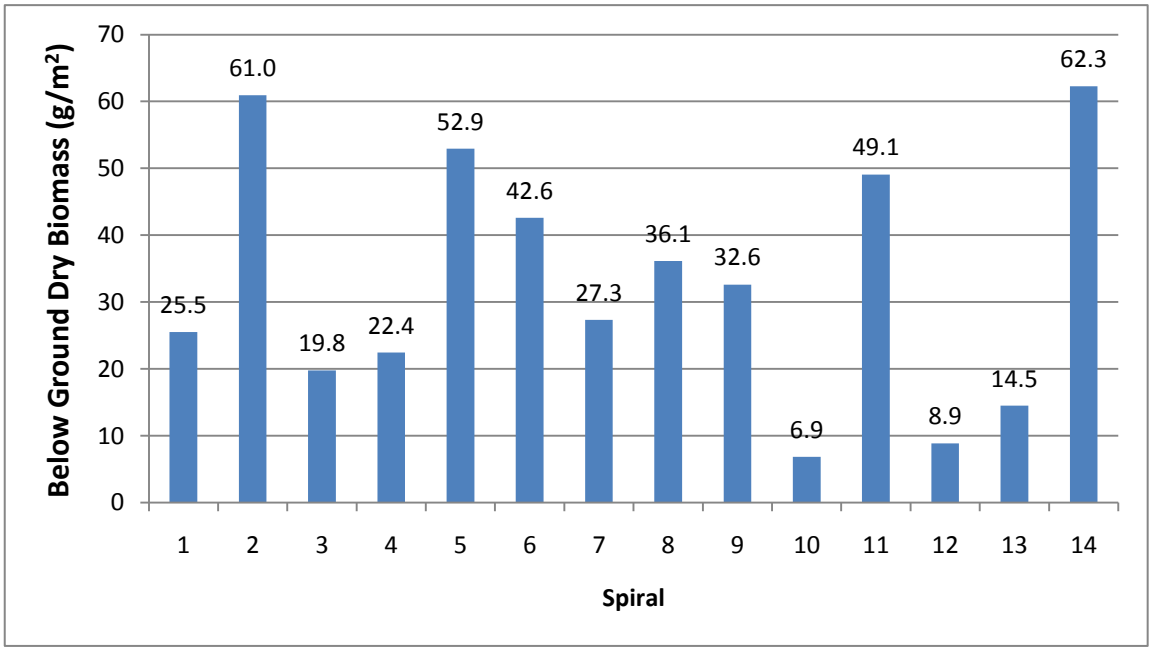


Figure 11. Below Ground Biomass by Spiral

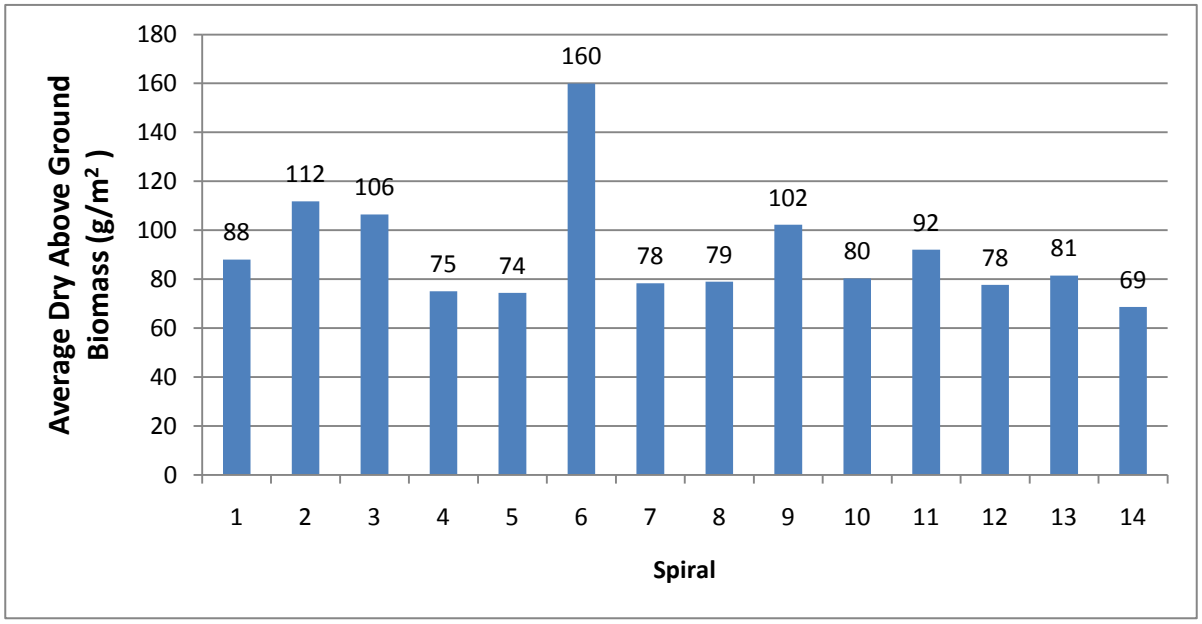


Figure 12. Above Ground Biomass by Spiral

Cone Index

Cone Index across all spirals averaged 594 kPa, with a high of 736 kPa and a low of 444 kPa (Figure 13).

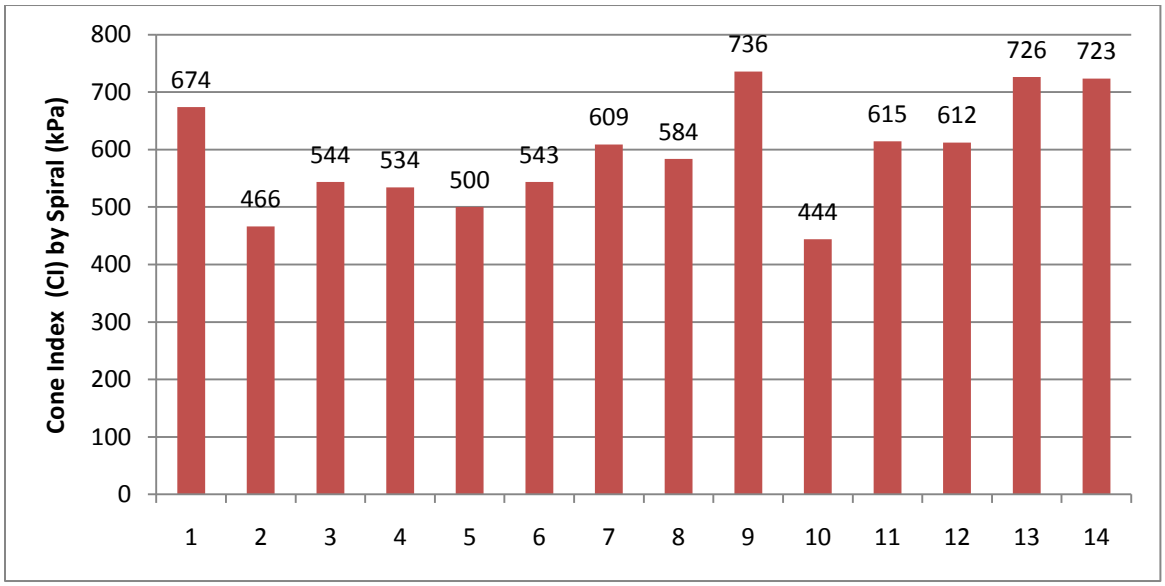


Figure 13. Cone Index (kPa) by Spiral

Drop Cone

Drop Cone across all spirals averaged 7.80 cm, with a high of 8.44 cm and a low of 7.24 cm (Figure 14).

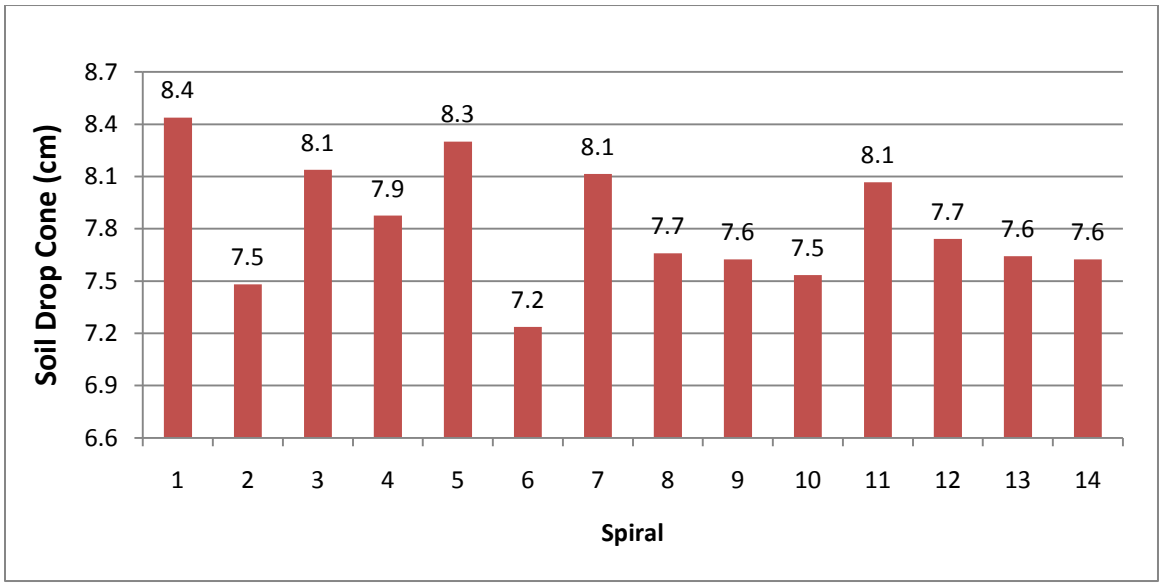


Figure 14. Soil Drop Cone by Spiral

Torsional Shear, Cohesion and Friction Angle

Shear Graph Torsional Shear (kPa) across all spirals averaged 18 kPa, with a high of 34 and a low of 2.0 kPa (Figure 15). Torsional Shear (C) ranged from a high of 4.95 to a low of 0.30 (Figure 16). Friction Angle (rad) ranged from a high of 0.64 to a low of 0.15 radians (Figure 17). TorVane Torsional Shear (kPa) across all spirals averaged 14 kPa, with a high of 17 and a low of 8.0 (Figure 18).

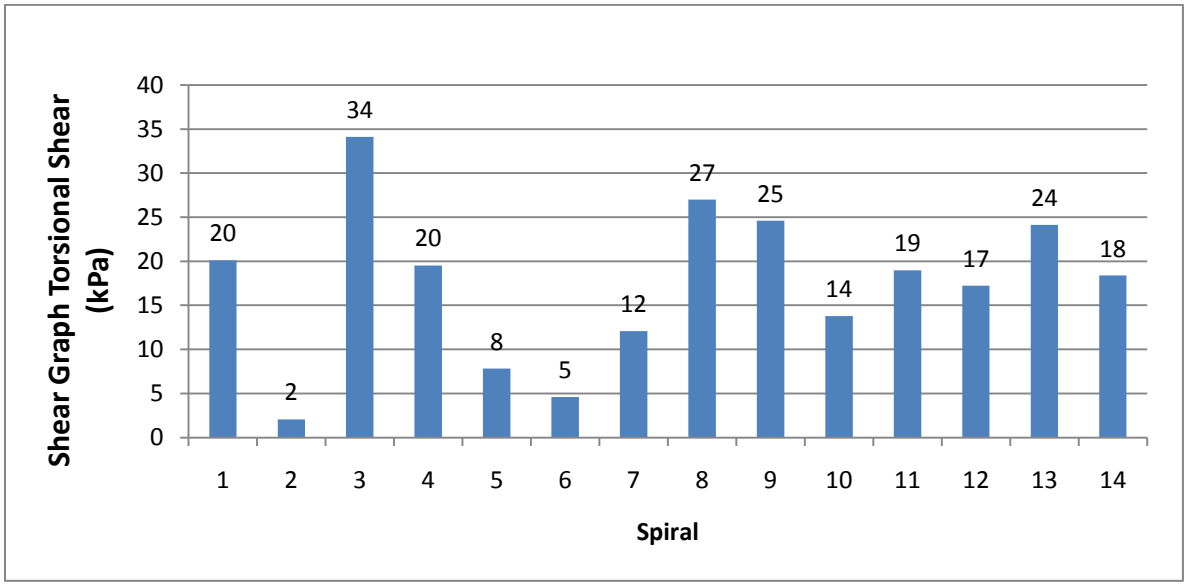


Figure 15. Shear Graph Torsional Shear (kPa)

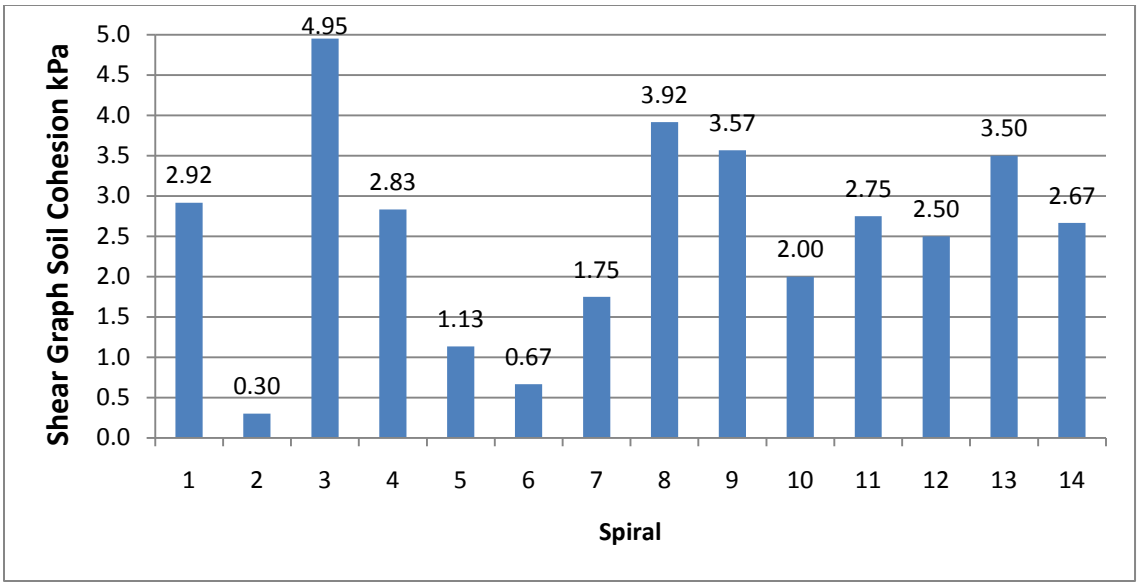


Figure 16. Shear GraphSoil Cohesion (kPa)

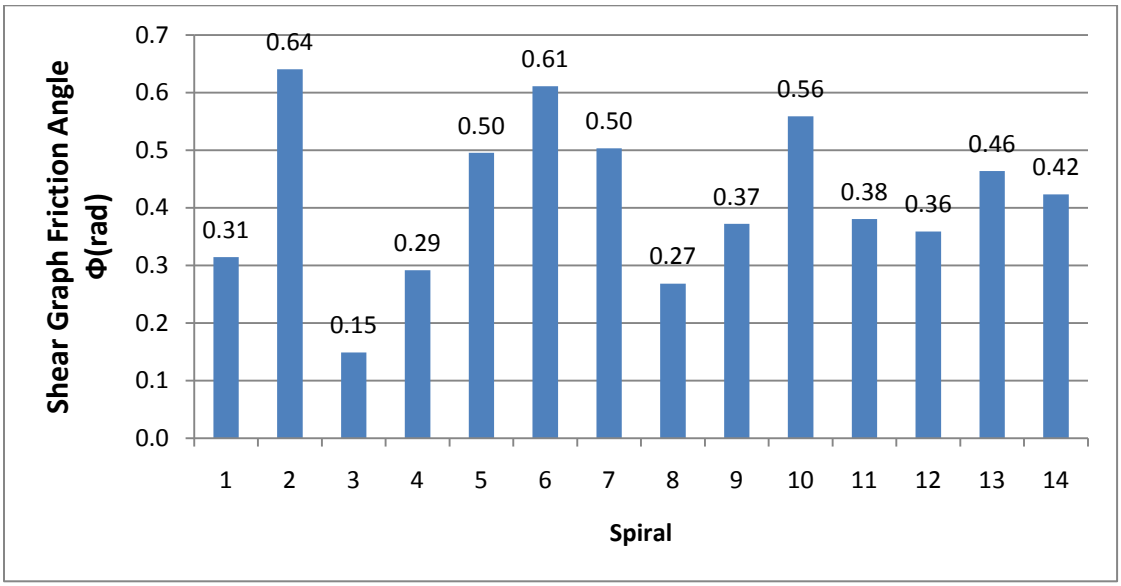


Figure 17. Shear Graph Friction Angle Φ(rad)

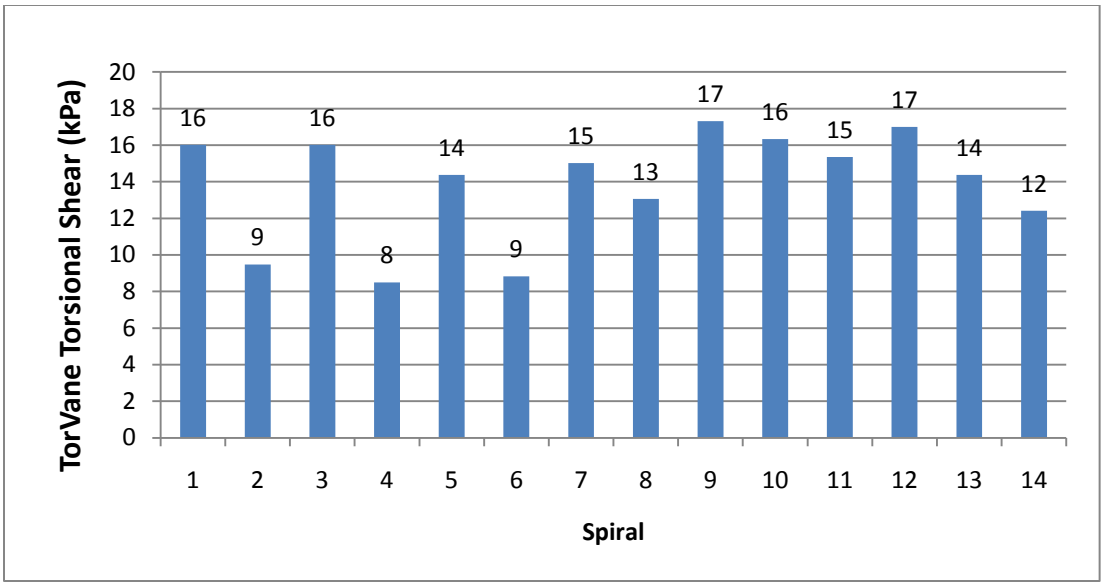


Figure 18. TorVane Torsional Shear by Spiral

Vehicle Dynamics and Terrain Impacts

Vehicle Disturbed Width, Impact Severity, and Cumulative Impact Width

Vehicle dynamics and terrain impact data collected consists of disturbed width (DW) in centimeters and impact severity (IS) on a scale of 0-100. DW was the disturbance of the vehicle track on the ground, and excluded vegetation piled next to the track edge. IS measures were determined by observing vegetation disturbances across the width of the vehicle track. Multiplying DW by IS gives cumulative impact width (CIW), a derived measure giving an indication of the width of vehicle track receiving 100% terrain impact. Thus, a vehicle which has a combined total of 100 cm of vegetation disturbed (from left and right-hand tracks or tires) at an impact severity of 20% will yield a CIW of 100 cm * 0.2, or 20 cm of the vehicle track with 100% damage. CIW is useful in determining percent vegetative cover removed and is an indication of soil erosion potential.

Vehicle Turning Radius Designations

Each vehicle's combined spirals (Table 3) was divided based on turning radius into three categories: straight turns, consisting of a turning radius exceeding 80 m, intermediate turns, consisting of a turning radius ranging from 30-80 m, and sharp turns, consisting of a turning radius of less than 30 m.

M1A1 Main Battle Tank

The M1A1 main battle tank was run on four spirals along a maximum of three consecutive pass observations (observations after one pass, two passes, and four passes) with 16 impact points per spiral, for a combined total of four spirals * three pass observations * 16 impact points = 192 total impact points. The M1A1 was not run to eight passes (as were the other vehicles) due to the severity of the vehicle terrain impacts on the wet soil at the testing location after four passes.

Across all passes, results indicated that initial CIW from the first pass increased more from the first to second pass than from the second to fourth pass, indicating that the majority of terrain impacts by the M1A1 were caused during the first and second passes (Table 4, Figure 19, Figure 20). 'OCIW' indicates outside, or driver side, and 'ICIW' indicates inside, or passenger side impacts.

Table 4. M1A1 Average CIW (cm) vs. TR

	PASS 1	PASS 2	PASS 4
STRAIGHT	45.7	83.0	110.3
INTERMEDIATE	100.9	148.2	178.0
SHARP	169.7	220.7	261.4

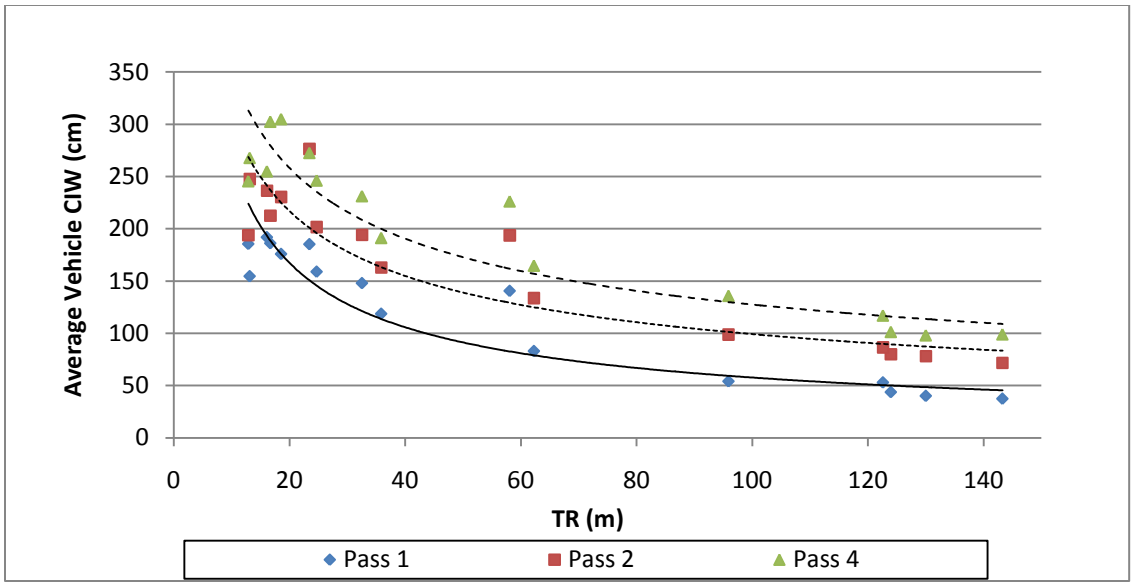


Figure 19. M1A1 Multipass Comparisons

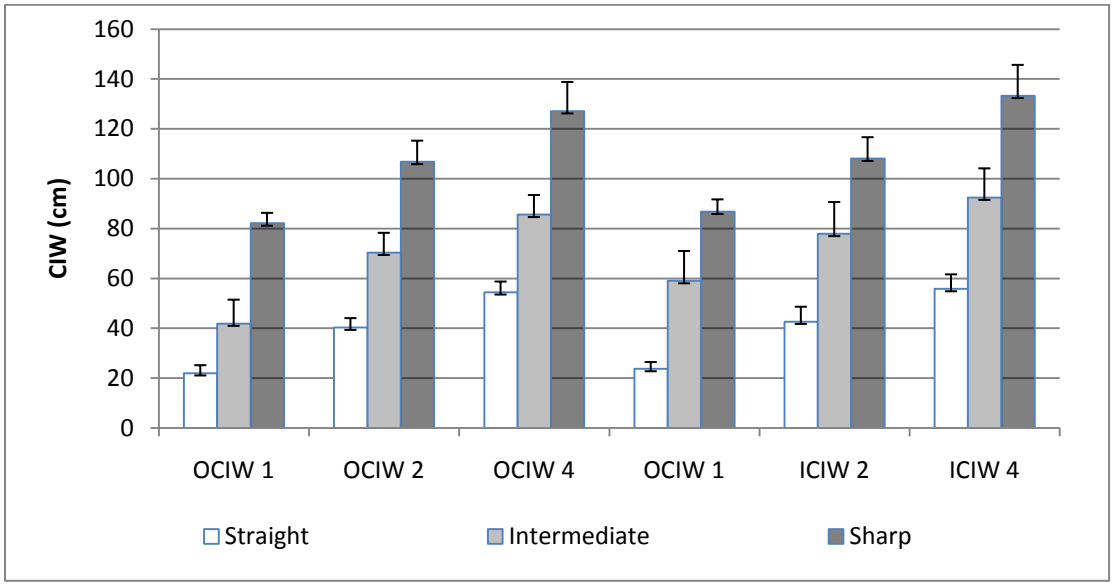


Figure 20. M1A1 CIW vs. TR. Error bars are 95% Confidence Intervals.

For the M1A1 among all consecutive passes, DW increased as the turning radius decreased from straight to intermediate turns, and increased substantially more as the turning radius decreased from intermediate to sharp turns (Figure 21). 'ODW' indicates outside, or driver side, and 'IDW' indicates inside, or passenger side impacts. DW was highest at sharp turns and was lowest along a straight path.

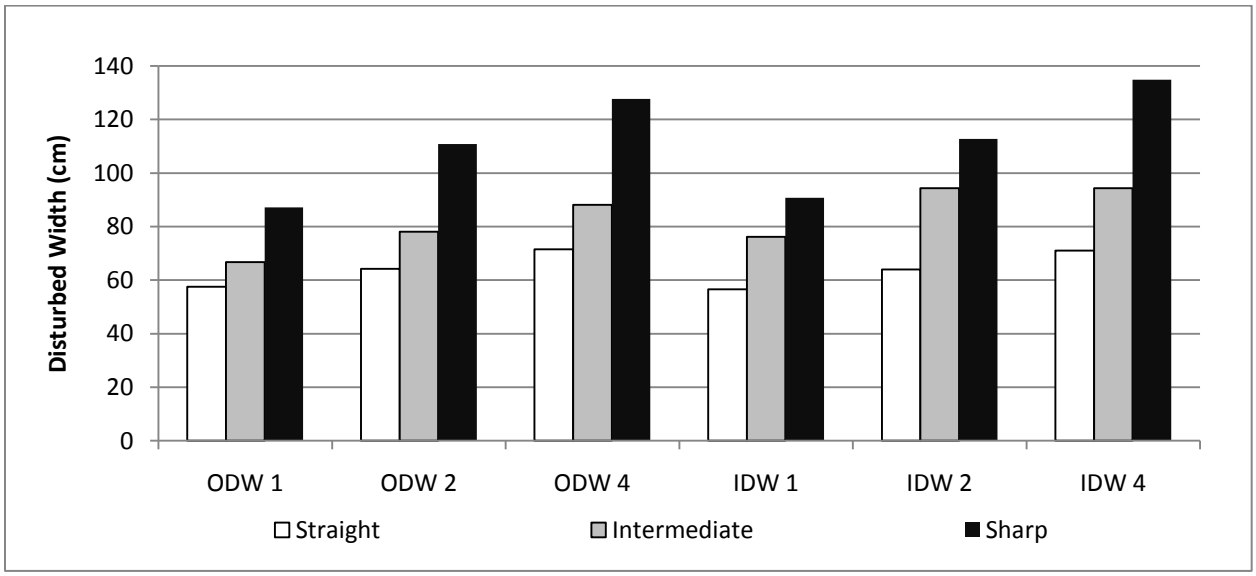


Figure 21. M1A1 DW vs. Turning Radius

In terms of IS, the severity of impact was substantially influenced by turning radius (Figure 22). 'OIS' indicates outside, or driver side, and 'IIS' indicates inside, or passenger side impacts.

As consecutive impacts occurred, however, the influence of IS was lessened, due to the preexisting damage caused by previous vehicle passes. IS was highest at sharp turns and was lowest along a straight path. Nearly 100% IS was reached after four passes.

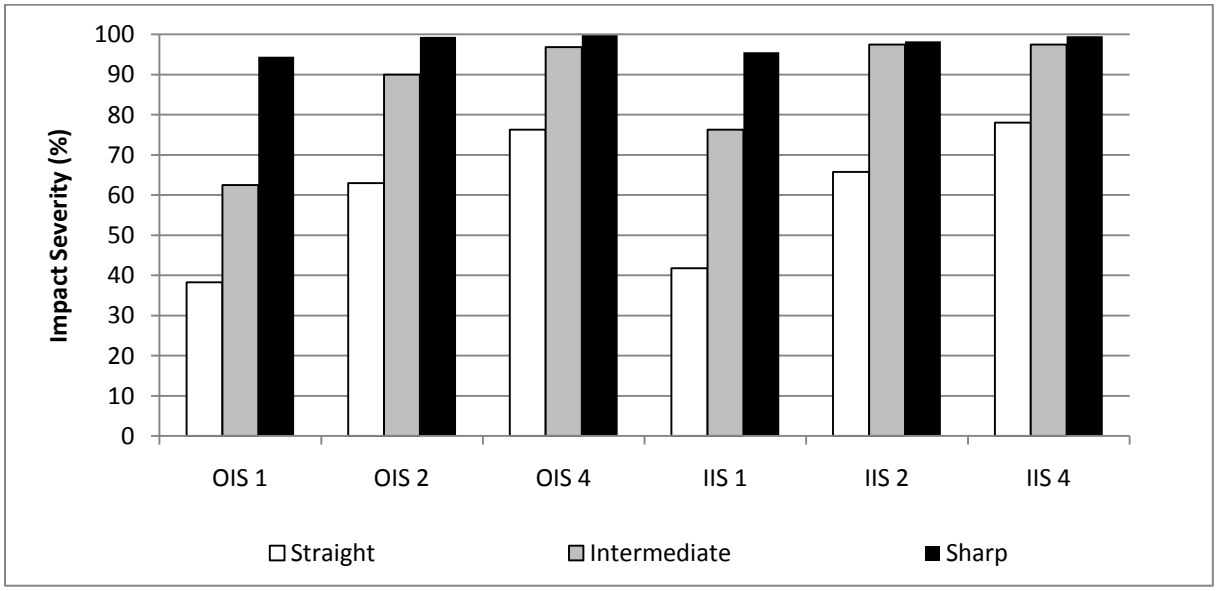


Figure 22. M1A1 IS vs. TR

M113 Armored Personnel Carrier (APC)

The M113 APC was run on three spirals along a maximum of four pass observations (observations after one pass, two passes, four passes and eight passes), with 14 impact points per spiral, for a combined total of three spirals * four pass observations * 14 impact points = 168 total impact points.

Across all passes, results indicated that initial CIW from the first pass increased linearly from the first to second, and from the second to fourth passes. A lesser increase was observed from the fourth to the eighth passes. This indicates that the majority of terrain impacts by the M113 were caused during the first four passes (Table 5, Figure 23- Figure 24). 'OCIW' indicates outside, or driver side, and 'ICIW' indicates inside, or passenger side impacts.

Table 5. M113 Average Vehicle CIW (cm) vs. TR

	Pass I	Pass II	Pass IV	Pass VIII
Straight	10.3	31.8	44.9	62.1
Intermediate	24.6	62.4	94.8	109.8
Sharp	59.0	90.8	125.9	150.9

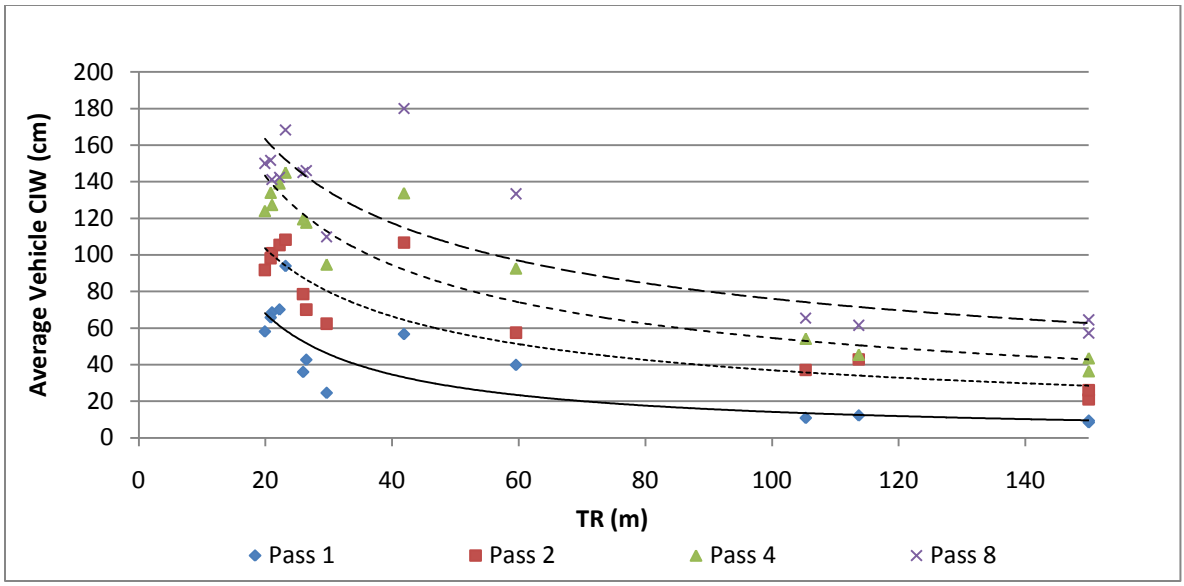


Figure 23. M113 Multipass Comparisons

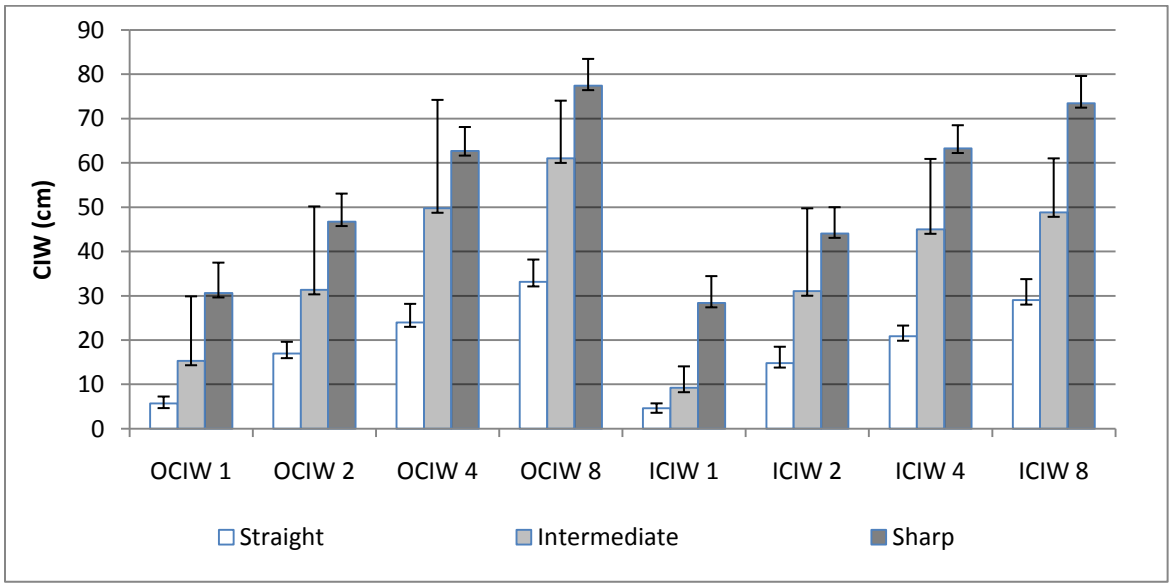


Figure 24. M113 CIW vs. TR. Error bars are 95% Confidence Intervals.

For the M113 among all consecutive passes, DW increased as the turning radius decreased from straight to intermediate turns, and tended to increase further as the turning radius decreased from intermediate to sharp turns following eight consecutive passes (Figure 25). Overall, the DW vs. TR trend for the M113 followed a near linear progression, with DW at all TR increasing as progressive impacts occurred. DW was highest at sharp turns (with the notable exception of the second consecutive pass for driver and passenger sides) and was lowest at straight turns. 'ODW' indicates outside, or driver side, and 'IDW' indicates inside, or passenger side impacts.

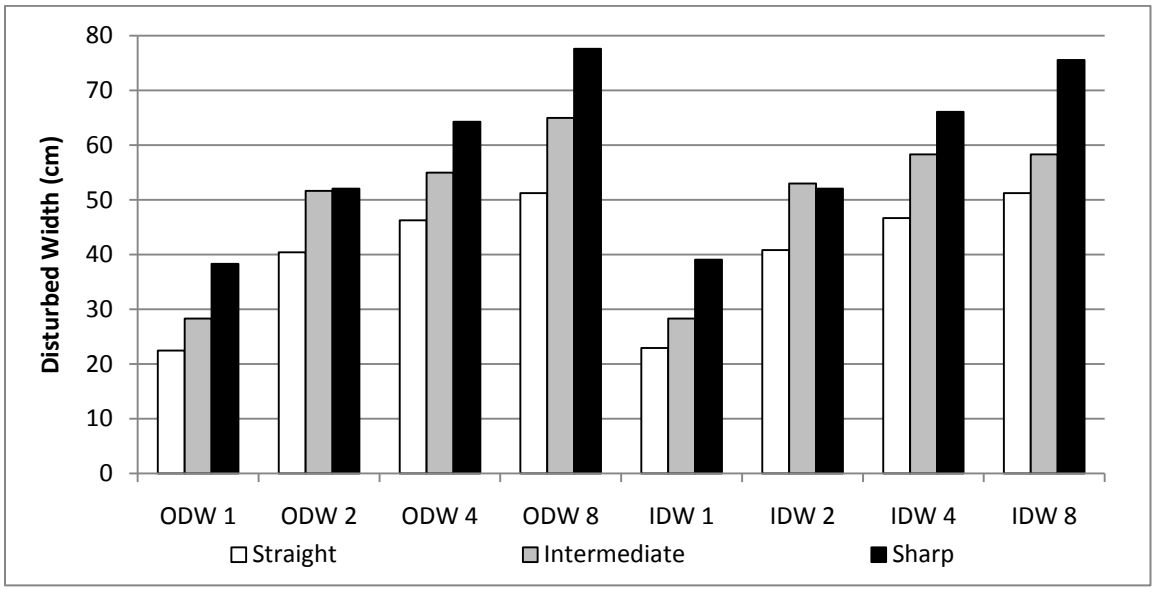


Figure 25. M113 DW vs. TR

In terms of IS, the severity of impact was directly related to the turning radius of the vehicle. Straight paths produced relatively small impacts, with impact severity increasing with both the decrease in turning radius and with consecutive passes.

The impact severity of sharp turns was much higher as compared with straight and intermediate turns, especially after the first and second consecutive pass. As consecutive impacts occurred, however, the influence of IS was lessened, perhaps due to the preexisting damage done by previous vehicle passes as the IS approached 100% (Figure 26). 'OIS' indicates outside, or driver side, and 'IIS' indicates inside, or passenger side impacts.

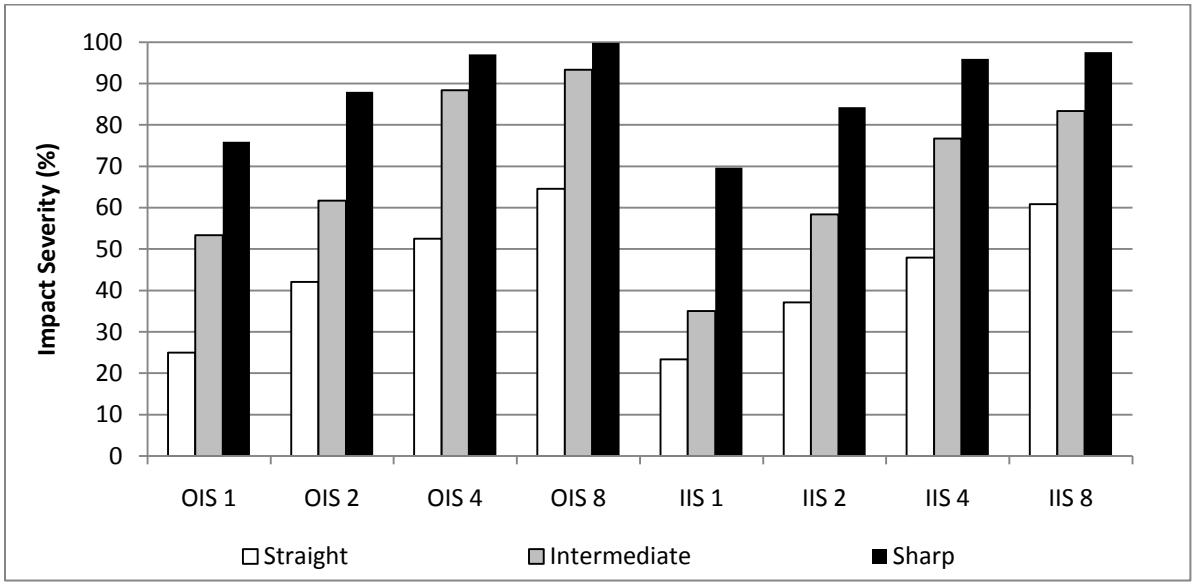


Figure 26. M113 IS vs. TR

M985 Heavy Expanded Mobility Tactical Truck (M985 HEMTT)

The M985 HEMTT was run on three spirals along a maximum of four pass observations (observations after one pass, two passes, four passes and eight passes), with 12 impact points per spiral, for a combined total of three spirals * four pass observations * 12 impact points = 144 total impact points.

Across all passes, results indicated that initial CIW from the first pass increased linearly across all passes, with the largest increase observed between the second and fourth passes. This indicates that terrain impacts by the M985 HEMTT increased incrementally as passes increased (Table 6, Figure 27). 'OCIW' indicates outside, or driver side, and 'ICIW' indicates inside, or passenger side impacts.

Table 6. M985 HEMTT Vehicle CIW (cm) vs. TR

	Pass I	Pass II	Pass IV	Pass VIII
Straight	23.7	59.0	85.9	130.1
Sharp	86.6	141.2	201.4	253.6

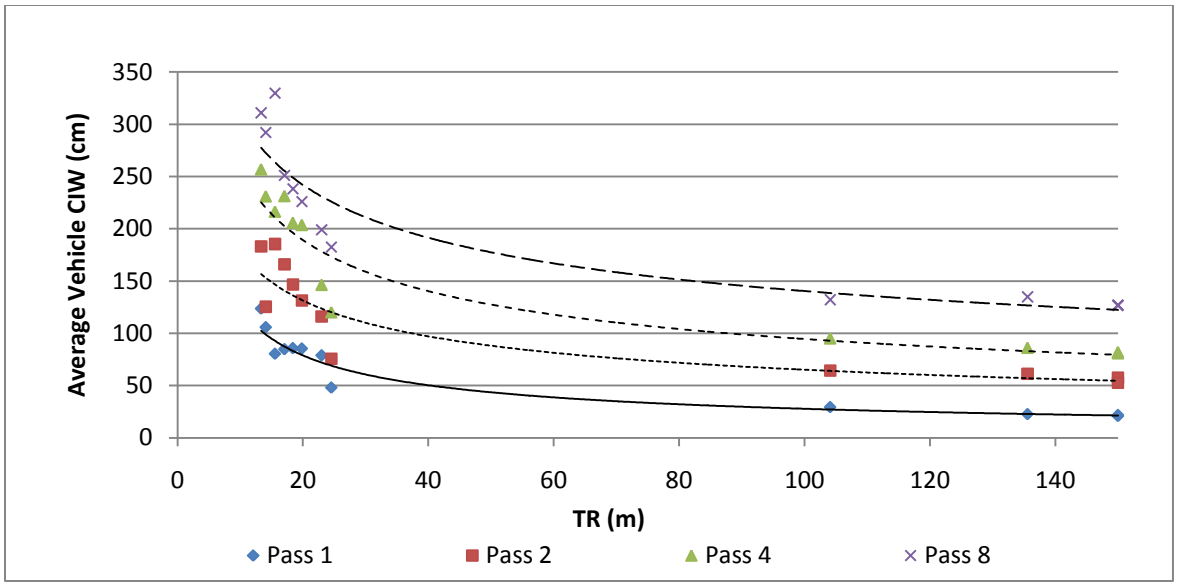


Figure 27. M985 HEMTT Multipass Comparisons

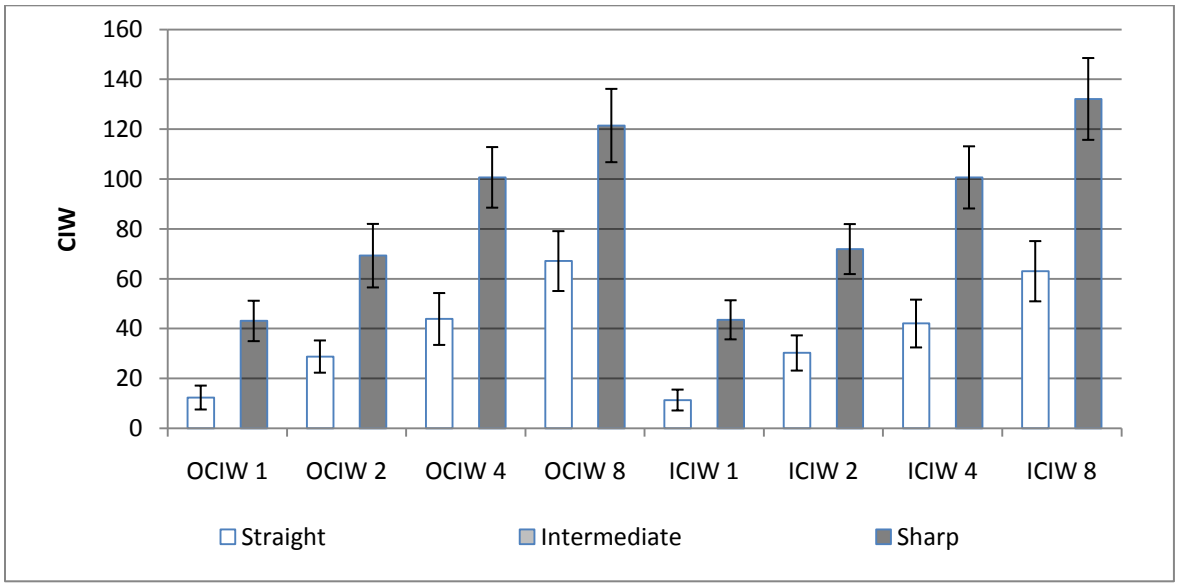


Figure 28: M985 HEMTT CIW vs. TR. Error bars are 95% Confidence Intervals.

For the M985 HEMTT among all consecutive passes, DW increased markedly as the turning radius decreased from straight to sharp turns, leveling off between the fourth and eighth consecutive passes (Figure 29). Overall, DW at all TR increased as progressive impacts occurred, with the exception of the sharp turn of the fourth to eighth consecutive pass of the driver's side, where the DW of the fourth consecutive pass was slightly larger than that of the eighth consecutive pass. In general, DW was highest at sharp turns and was lowest along straight paths. 'ODW' indicates outside, or driver side, and 'IDW' indicates inside, or passenger side impacts.

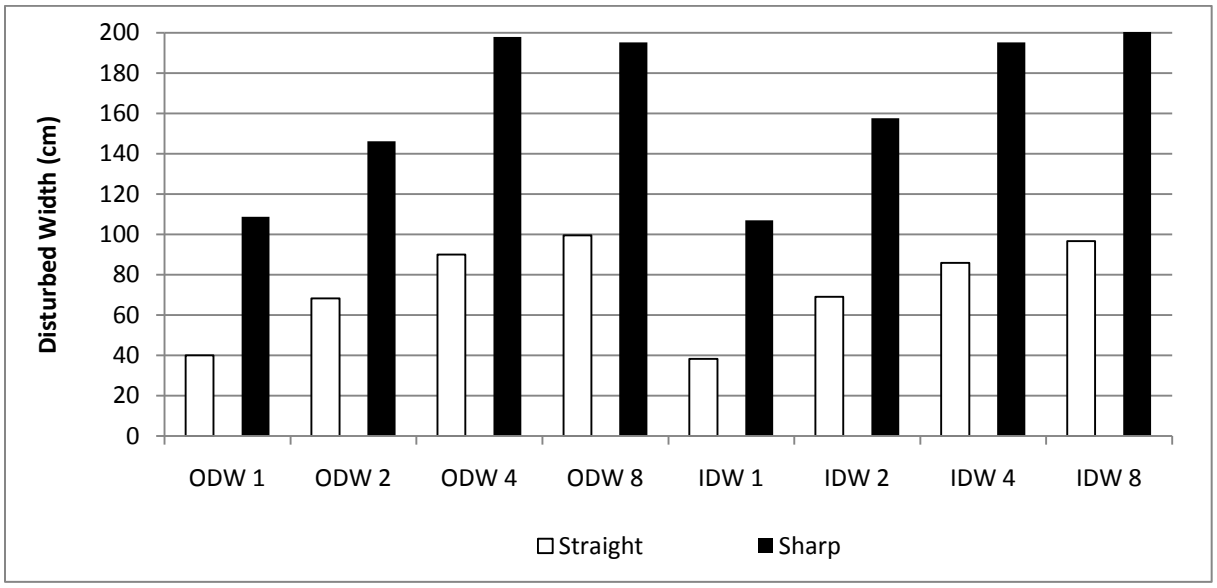


Figure 29. M985 HEMTT DW vs. TR

In terms of IS, the severity of impact was remarkably similar across the turning radius of the vehicle. With the exception of the first pass, straight turns and sharp turns produced relatively similar impacts, with impact severity increasing only slightly with the decrease in turning radius. IS increased following consecutive passes (Figure 30). 'OIS' indicates outside, or driver side, and 'IIS' indicates inside, or passenger side impacts.

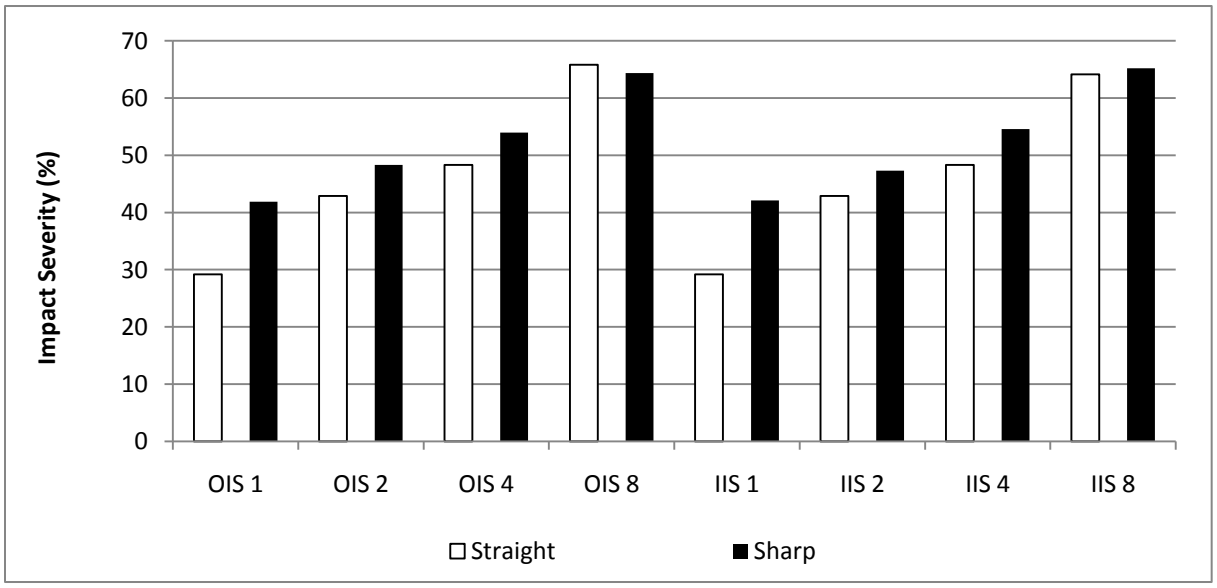


Figure 30. M985 HEMTT IS vs. TR

M998 High Mobility Multipurpose Wheeled Vehicle (M998 HMMWV)

The M998 HMMWV was run on four spirals along a maximum of four consecutive pass observations (observations after one pass, two passes, four passes and eight passes), with 12 impact points per spiral, for a combined total of four spirals * four pass observations * 12 impact points = 144 total impact points.

Across all passes, results indicated that initial CIW from the first pass increased linearly across all passes, with the largest increase observed between the second and fourth passes. This indicates that terrain impacts by the M998 HMMWV were fairly evenly distributed across all passes. CIW was highest at sharp turns and was lowest at straight turns (Table 7, Figure 32). 'OCIW' indicates outside, or driver side, and 'ICIW' indicates inside, or passenger side impacts.

Table 7. M998 HMMWV Vehicle CIW (cm) vs. TR.

	Pass I	Pass II	Pass IV	Pass VIII
Straight	6.2	16.1	31.8	44.2
Intermediate	7.1	25.1	57.4	67.3
Sharp	13.5	39.1	72.5	120.9

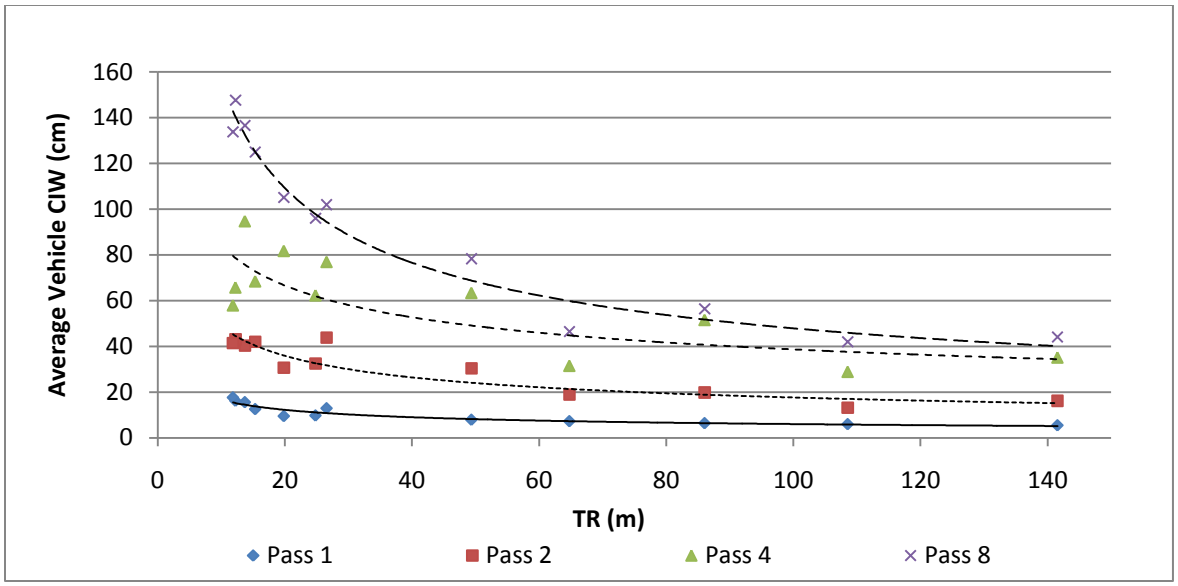


Figure 31. M998 HMMWV Multipass Comparisons

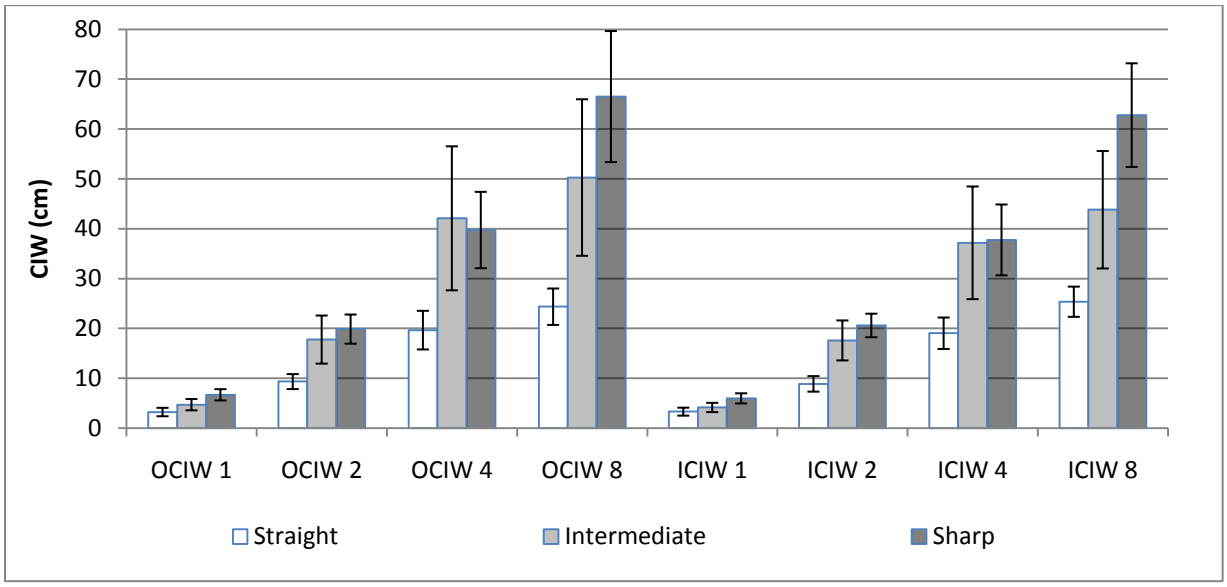


Figure 32. M998 HMMWV CIW vs. TR. Error Bars are 95% Confidence Intervals.

For the M998 HMMWV among all consecutive passes, DW increased as the turning radius decreased from straight to sharp turns (Figure 33). Overall, DW at all TR increased as progressive impacts occurred. Some flattening of DW was noted for straight and intermediate turns between the fourth and eighth passes, while for sharp turns, DW increased as the number of passes increased. In general, DW was highest at sharp turns and was lowest along straight paths. 'ODW' indicates outside, or driver side, and 'IDW' indicates inside, or passenger side impacts.

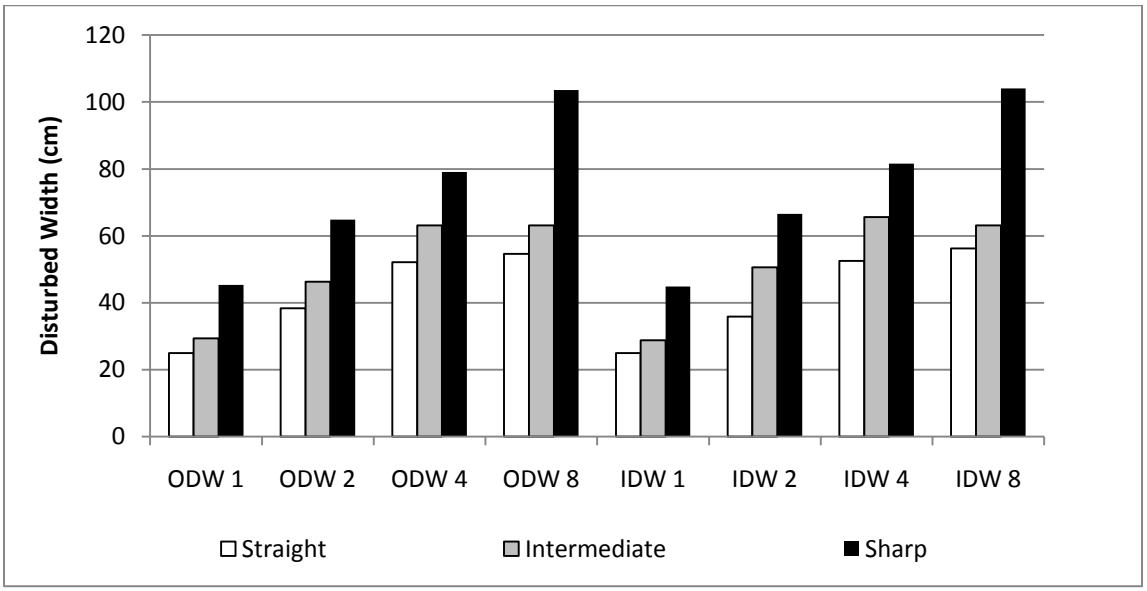


Figure 33. M998 HMMWV DW vs. TR.

In terms of IS, the severity of impact was similar among turning radii at the first and second passes. Overall, impact severity increased with the decrease in turning radius and

increased following consecutive passes (Figure 34). 'OIS' indicates outside, or driver side, and 'IIS' indicates inside, or passenger side impacts.

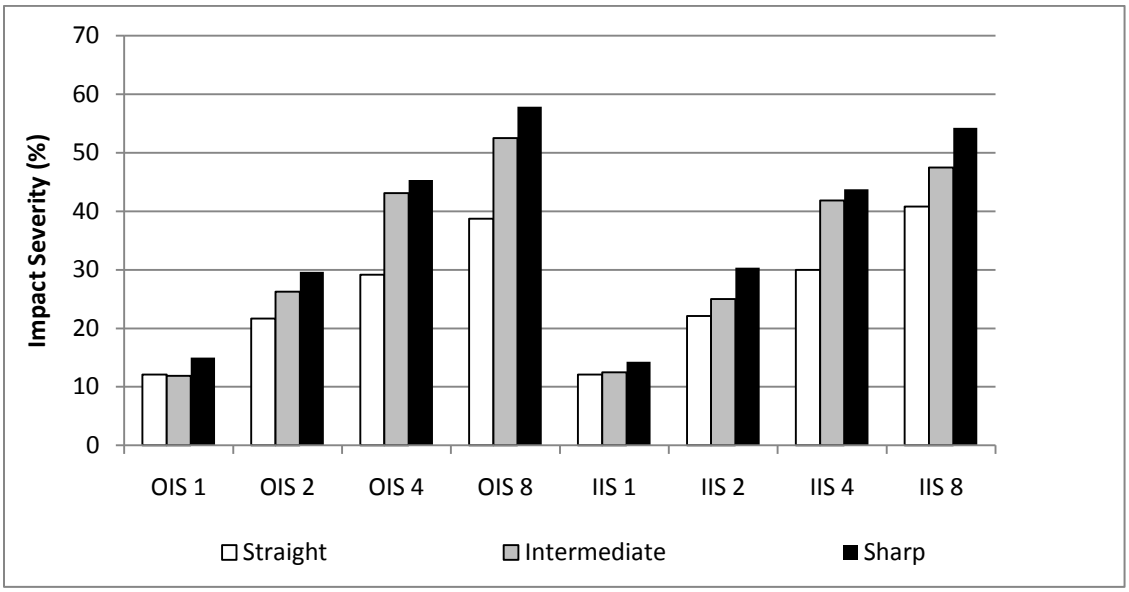


Figure 34. M998 HMMWV IS vs. TR.

Multipass Coefficient Results

Multipass coefficients determined using the statistical analysis program JMP are listed below (Table 8).

Table 8. Calculated Multipass Coefficients and Error by Vehicle and Turning Radius

	Turning Radius	Number of points	First Pass CIW (cm)	MPC (a)	Average Error	Average Total Error	Average Percent error (%)
M1A1	straight	20	45.7	1.57	15.83	5.87	16.10
	intermediate	8	100.9	3.10	25.00	3.92	15.96
	sharp	36	169.7	4.44	43.66	6.60	17.44
M113	straight	12	10.3	1.13	18.11	6.70	39.55
	intermediate	3	24.6	1.34	37.30	13.50	36.75
	sharp	27	59.1	2.31	38.20	11.68	30.48
M985 HEMTT	straight	12	23.7	1.18	31.14	5.85	32.79
	intermediate	n/a	n/a	n/a	n/a	n/a	n/a
	sharp	24	86.6	2.13	59.33	26.75	29.55
M998 HMMWV	straight	12	6.2	1.04	14.12	9.51	39.01
	intermediate	8	7.1	0.98	24.21	15.53	44.72
	sharp	28	13.5	1.07	36.26	21.55	45.92

Table 9. Average Error of MPC = 2.00 and Percent Error Reduction using Calculated MPC

Vehicle	TR	Average Error (MPC = 2.0)	Percent Error Reduction (Calc. MPC)
M1A1	Straight	21.79	27.35
M1A1	Intermediate	26.43	5.43
M1A1	Sharp	129.59	66.31
M113	Straight	24.90	27.27
M113	Intermediate	37.82	1.39
M113	Sharp	42.08	9.23
M985 HEMTT	Straight	42.51	26.74
M985 HEMTT	Sharp	59.16	-0.30
M998 HMMWV	Straight	23.78	40.60
M998 HMMWV	Intermediate	35.12	31.06
M998 HMMWV	Sharp	50.77	28.57

Multipass Coefficient Validation: Field Data vs. Predicted Results

Using the MPC determined using the statistical analysis program JMP and the measured CIW from the field, new predicted CIWs were calculated and plotted against the original data. A spread close to the 1:1 line of each figure is an indication that the MPC capable of successful CIW prediction (Figs. 35-45).

M1A1 Main Battle Tank

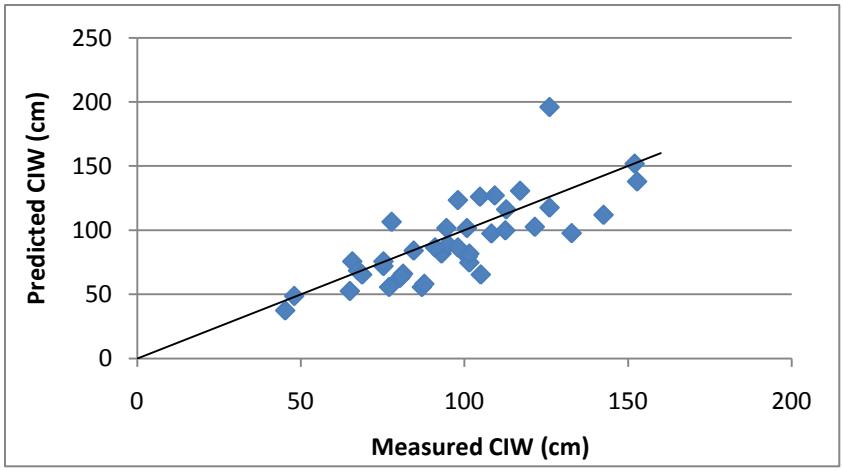


Figure 35. M1A1 Straight Predicted vs. Measured CIW

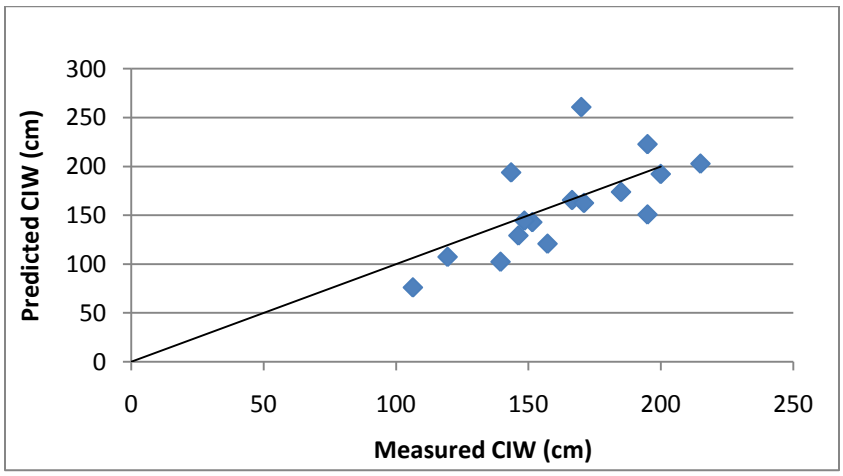


Figure 36. M1A1 Intermediate Predicted vs. Measured CIW

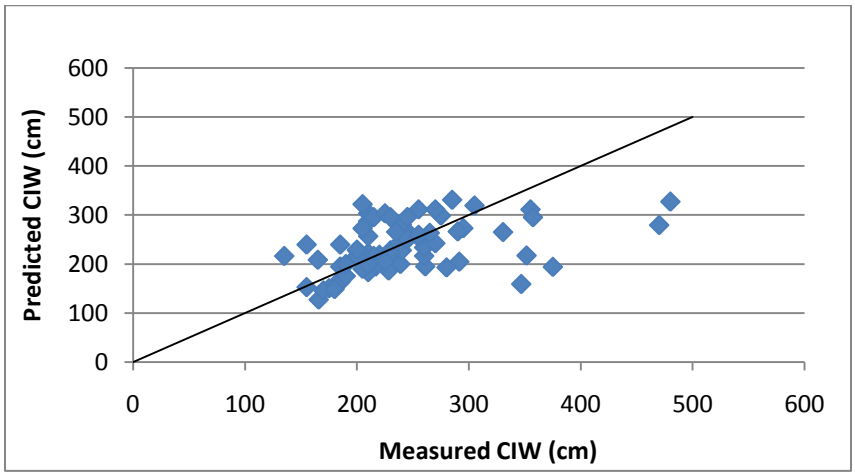


Figure 37. M1A1 Sharp Predicted vs. Measured CIW

M113 Armored Personnel Carrier (APC)

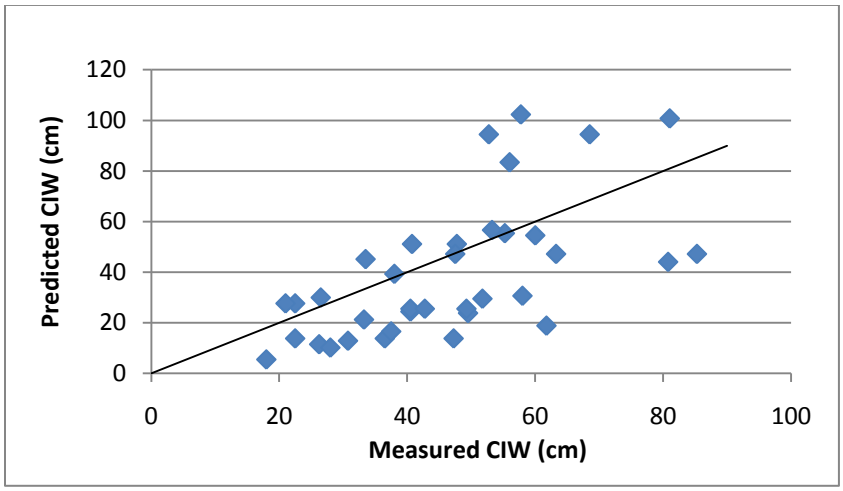


Figure 38. M113 Straight Predicted vs. Measured CIW

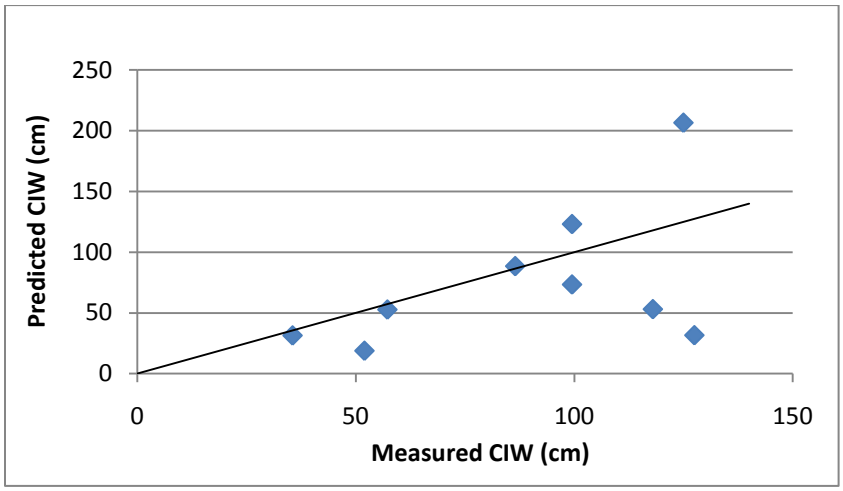


Figure 39. M113 Intermediate Predicted vs. Measured CIW

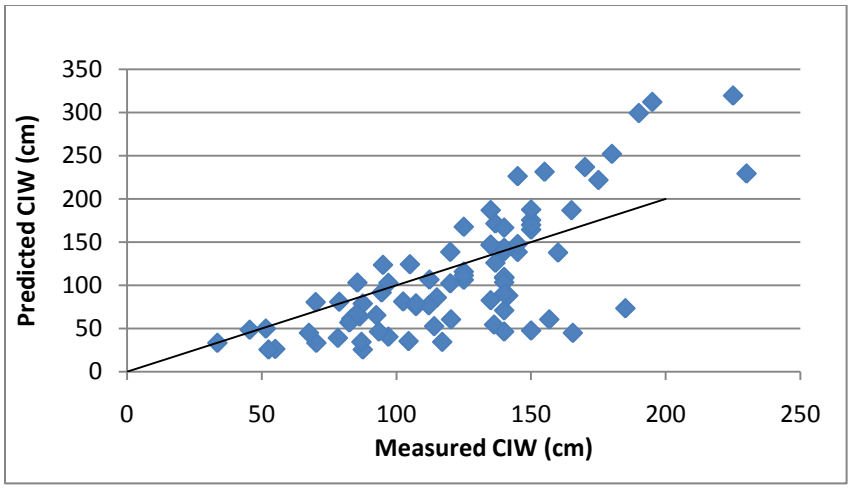


Figure 40. M113 Sharp Predicted vs. Measured CIW

M985 Heavy Expanded Mobility Tactical Truck (M985 HEMTT)

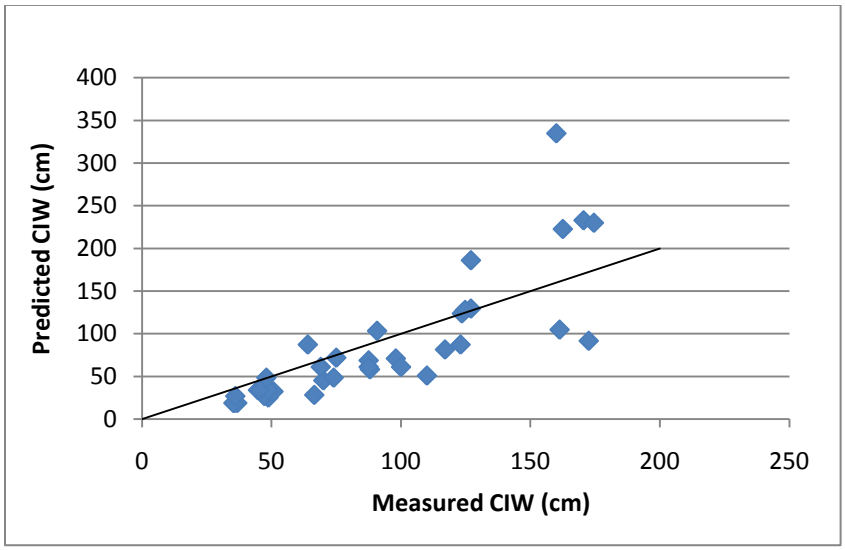


Figure 41. M985 HEMTT Straight Predicted vs. Measured CIW

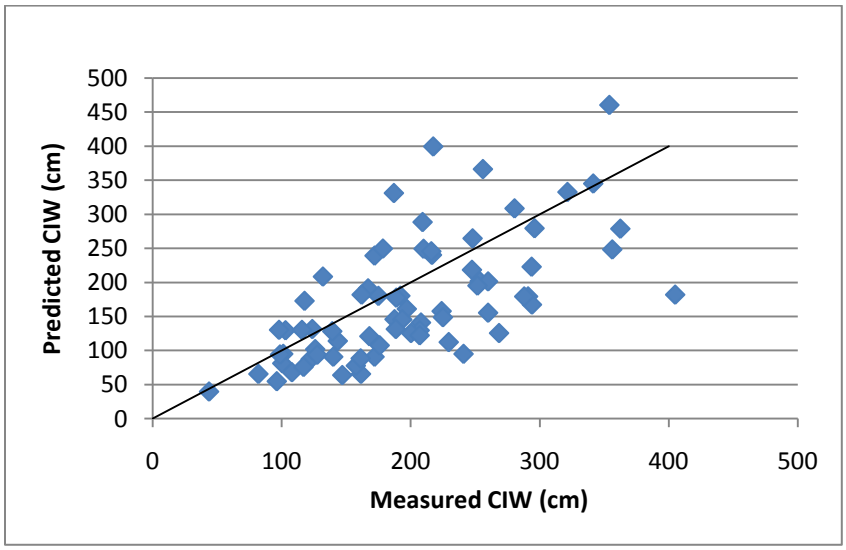


Figure 42. M985 HEMTT Sharp Predicted vs. Measured CIW

M998 High Mobility Multipurpose Wheeled Vehicle (M998 HMMWV)

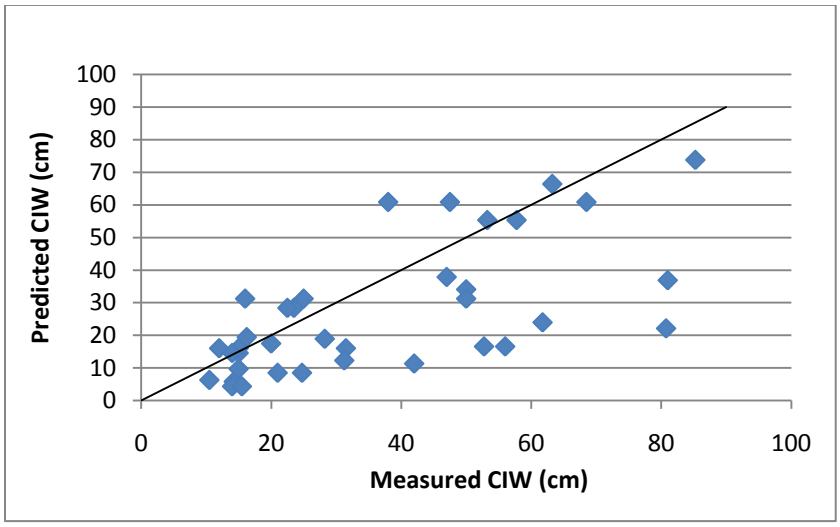


Figure 43. M998 HMMWV Straight Predicted vs. Measured CIW

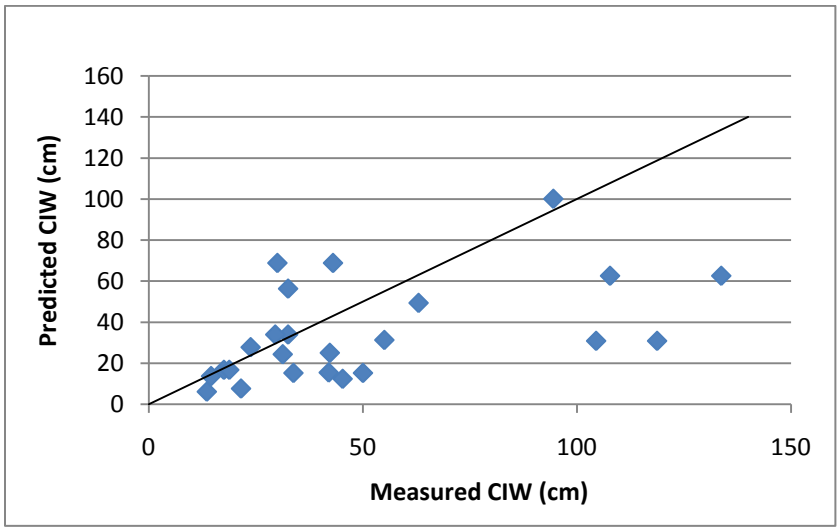


Figure 44. M998 HMMWV Intermediate Predicted vs. Measured CIW

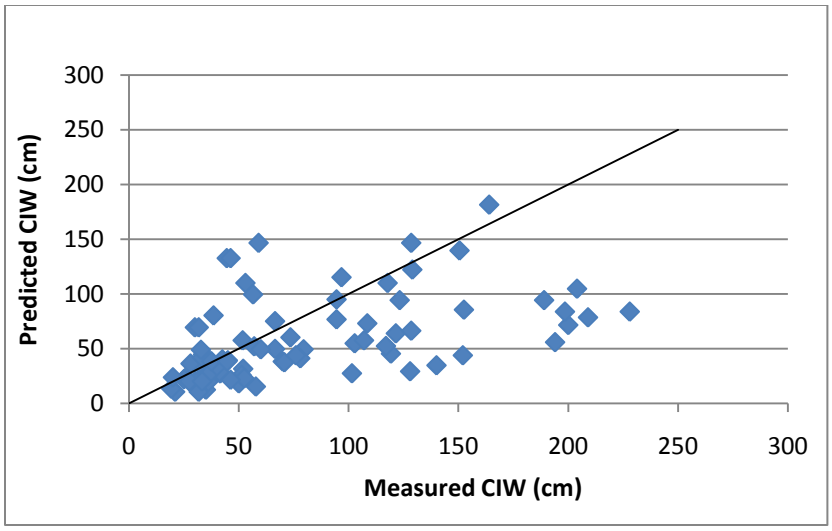


Figure 45. M998 HMMWV Sharp Predicted vs. Measured CIW

Discussion

Vehicle Dynamics- Terrain Impacts

Several trends were visible from comparisons between vehicle mobility mechanisms and vehicle sizes. In terms of CIW vs. TR (Figure 46), the largest vehicles, such as the M1A1 and M985 HEMTT, were associated with the largest CIW at small turning radii (below 50 meters). At larger radii (above 100 meters), a difference in impacts was noted between tracked and wheeled vehicles, as the M113, a light tracked vehicle, caused more terrain damage than the larger wheeled M985 HEMTT.

From this, two main points can be generalized. One, that large and/or heavy vehicles create more terrain and vegetative disturbance than do small vehicles, especially at smaller turning radii, and two, that tracked vehicle impacts are more severe than wheeled vehicle impacts, especially at large radius turns or along straight paths. These results further verify the findings of previous studies such as Ayers (1994), Affleck et al. (2004), and Althoff and Thien (2005) in terms of the relationship between turning radius and soil disturbance.

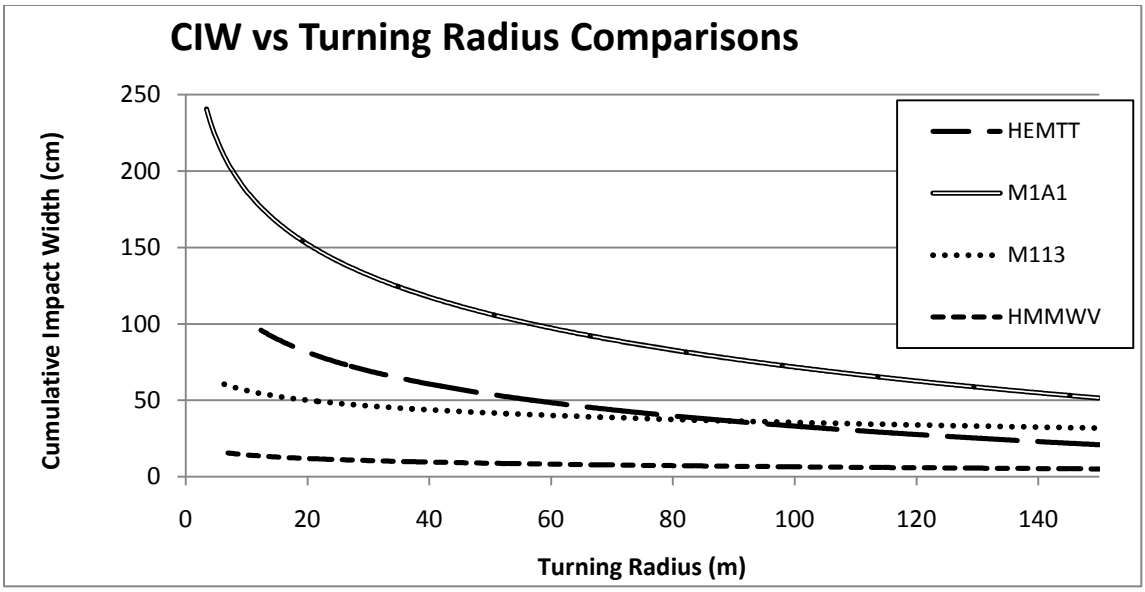


Figure 46. CIW vs. TR, All Vehicles

Vehicle Dynamics- Multipass Coefficients

In order to answer the question of whether or not TR influences MPC (by vehicle), single classification ANOVA was run, comparing MPCs for straight, intermediate, and sharp turning conditions for each vehicle. This analysis showed that MPCs for the M1A1 are statistically significant, with a p value of 0.0013. MPCs for the M113 are statistically significant, with a p value of 0.004. MPCs for the M985 HEMTT are statistically significant, with a p value of 0.0091. Single classification ANOVA failed to show that MPCs for straight, intermediate, and sharp turning conditions for the M998 HMMWV were statistically significant, with a p value of 0.8315. Analysis shows that TR influences MPC for all study vehicles except the M998 HMMWV.

In order to answer the question of whether or not differences exist between MPCs by vehicle, unpaired t-tests were run. Statistically significant differences were found between averaged MPCs at all turning radii of the M1A1 and M133, M1A1 and M985 HEMTT and the M1 and M998 HMMWV, with p values of 0.0023, 0.0023, and less than 0.0001 respectively. Statistically significant differences were found between averaged MPCs at all turning radii between the M113 and M998 HMMWV and the M985 HEMTT and M998 HMMWV, with P values of less than 0.0001. Statistically significant differences were not found between the M113 and M985 HEMTT, with a p value of 0.6578. These statistical differences suggest that the calculated MPCs for each vehicle by turning condition can be associated with actual differences in vehicle impacts on terrain, and that the calculated MPCs can be used to more accurately assess differing vehicle impacts by associating those vehicles and their impacts with unique MPCs- with the caveat that the MPCs for the M985 HEMTT and M113 must be assumed to be

the same, as no statistical differences were found between them. As it is unlikely that the populations are identical, the differences may have gone undetected due to the small sample size and high variability in the field data for the M985 HEMTT and M113. The M985 HEMTT is heavier than the M113, but the M113 is a tracked vehicle.

Multipass coefficients for specific turning radii differed between and within vehicles. In general, calculated MPCs increased as turning radius decreased, with the exception of the M998 HMMWV, which showed no increasing trend.

Differences were observed between wheeled and tracked vehicle MPCs. When large/small vehicles are compared, tracked vehicles have a larger MPC for both sharp turns and along straight paths. The widely-used MPC of 2.00 (as described by Saarilahti, 2003) fits the M985 HEMTT and M113 at sharp turns, with an MPC of 1.00 fitting the straight and intermediate turning conditions of these vehicles, as well as all turning conditions for the M998 HMMWV (Table 8). For the M1A1, a MPC of 2.00 is suitable for straight paths, a MPC of 3.00 is suitable for intermediate turns, while sharp turns can be represented by a MPC of 4.00. According to the data, the widely-used MPC of 2.00 is not a good estimate for representing vehicle terrain impacts or for predicting vehicle impacts in the field. Calculated MPCs ranged from less than 1.00 to over 4.00. The data suggests that MPCs should be adjusted depending on the vehicle type and according to the turning radius of the vehicle.

Vehicle Dynamics- Multipass Coefficient Validation

In order to evaluate newly calculated MPCs, average error, average total error, and average percent error were calculated for each vehicle TR (Table 8).

Average error for the M1A1 at all turning radii ranged from a low of 15.83 to a high of 43.66. Average percent error for the M1A1 at all turning radii ranged from a low of 15.96 to a high of 17.44.

Average error for the M113 at all turning radii ranged from a low of 18.11 to a high of 38.20. Average percent error for the M113 at all turning radii ranged from a low of 30.48 to a high of 39.55.

Average error for the M985 HEMTT at all turning radii ranged from a low of 31.14 to a high of 59.33. Average percent error for the M985 HEMTT at all turning radii ranged from a low of 29.55 to a high of 32.79.

Average error for the M998 HMMWV at all turning radii ranged from a low of 14.12 to a high of 36.26. Average percent error for the M998 HMMWV at all turning radii ranged from a low of 39.01 to a high of 45.92.

Taking into account the wide variation in field data, these calculated errors indicate that the calculated MPCs allow for reasonably accurate prediction of vehicle CIW at a wide range of turning radii. Additionally, calculated errors for calculated MPCs compare favorably with errors for the commonly-accepted MPC of 2.00 in terms of percent error reduction (Table 9). In only one instance (M985 HEMTT Sharp) did the calculated MPC fail to reduce percent error. It should

be noted, however, that the percent error reduction of a MPC = 2.00 compared to the calculated MPC is less than one percent (Table 9).

Based on this validation, calculated MPCs allow for better and more realistic estimations of CIW than does the commonly-accepted MPC of 2.00. With few exceptions, using calculated MPCs will allow for better prediction of vehicle impacts at all turning radii and multipass conditions.

In general, predicted values versus field data fit a 1:1 line when plotted against one another, with expected scatter due to the wide variation in field data (Figure 35- Figure 45). With improved MPCs, the model is able reflect observed field trends. Calculated MPCs are valid for the range of multiple passes tested.

CHAPTER V: Conclusions

Future Work

In conclusion, this project was able to evaluate the terrain impacts of four commonly used tracked and wheeled military vehicles across one, two, four and eight passes along the same path at a given velocity and turning radius. Additionally, this project was able to determine multipass coefficients for vehicles as a modification to the predictive CIW equation.

Overall, this represents an important step towards a more complete, in-depth understanding of vehicle/terrain interactions. This project validated the efficacy of using simple, straightforward techniques to give accurate estimates of vegetation and terrain disturbances, as well as the continued utility of the simple predictive CIW equation originally intended for use with vehicle rutting. This and other projects will permit military land managers to quickly determine the extent and severity of terrain impacts and make decisions accordingly in line with long-term training sustainability of the installation as a priority. Extrapolation of results from this or other studies may be used to encompass widely different terrains and soil types, moisture regimes or ecosystem types.

In the future, advances in rapid, real-time on-the-fly determinations of terrain disturbance either for individual vehicles or for large-scale training exercises may be developed. By using integrated GPS and radio-frequency packages, such as the in-development Army DFirst or Cybernet systems for vehicle tracking, it may one day be possible to automatically generate installation training disturbance maps for use by land management personnel, streamlining the

process of assessment and restoration efforts. A major limitation of this study was the limited availability of military vehicles. In the future, obtaining vehicles for an extended amount of time would be useful, as additional vehicle passes could be conducted in order to find the maximum limitations for vehicle DW. Additionally, more vehicle types could be tested.

More importantly, this study dealt with only one soil type and condition: a moist clay loam. As previous studies have concluded that wet soils are more susceptible to vegetative and terrain impacts, it would be valuable to repeat this study on different soil types, or on the same soil type under different conditions, such as extremely wet or dry conditions.

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VITA

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