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AN EVALUATION OF LOW-IMPACT TIRES ON MILITARY LANDS

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AN EVALUATION OF LOW-IMPACT TIRES ON MILITARY LANDS

1. Purpose. This Public Works Technical Bulletin (PWTB) transmits laboratory, field, and observational data obtained from evaluation of several low impact tires currently being used by land managers on several installations.

2. Applicability. This PWTB applies to all U.S. Army facilities engineering activities.

3. References.

a. Army Regulation (AR) 200-3, Environmental Quality, Natural Resources–Land, Forest and Wildlife Management, 28 February 1995, as modified 20 March 2000.

b. Arthur, A.M., 1996. Evaluation of turf tire sipe density on traction performance and turf damage. M.S. thesis. Knoxville, Tennessee: The University of Tennessee.

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d. Carrow, R.N. and B.J. Johnson. 1989. “Turfgrass wear as affected by golf cart tire design and traffic patterns.” *J Amer. Soc. Hart. Sci.* 114(2):240-246.

e. Gill, W.R. and G.E. Vandenburg. 1962. Soil dynamics in tillage and traction. Agricultural Handbook No. 316. U.S. Printing Office, Washington, DC: USDA-ARS.

f. Haugen, L., P.D. Ayers, M. Vance, and A. Anderson. 2000. Using GPS for vehicle tracking and dynamic property monitoring. ASAE Paper No. 001071. St. Joseph, MI: ASAE.

g. Kising, A. and H. Gohlich. 1989. Dynamic characteristics of large tyres. *J. Agricultural Engr Research* 43(1):11-21.

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i. Lines, J.A. and K. Murphy. 1991. The radial damping of agricultural tractor tyres. *J Terramechanics* 28(2-3):229-241.

j. Raper, R.L., A.C. Bailey and E.C. Burt. 1994. Prediction of soil stresses caused by tire inflation pressures and dynamic loads. American Society of Agricultural Engineers (ASAE) Paper No. 941547. St. Joseph, MI.

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4. Discussion.

a. AR 200-3 requires that installations be good stewards of land resources by controlling sources of dust and hydrological erosion from facilities to prevent damage to the land, water resources, and equipment. The Sikes Act also has provisions for no net loss of training lands through military training impacts. The Clean Water Act (CWA) and Clean Air Act (CAA) also have an impact on the way the military trains. To ensure compliance with CWA and CAA, the military tries to reduce their foot print in ways that reduce sediments and airborne dust generated during training activities. Programs such as Land Rehabilitation and Maintenance (LRAM) and Land Condition Trend Analysis (LCTA) have been established to help meet compliance requirements. These programs can affect the land for which they are stewards, so managers are using off-the-shelf technologies to reduce their footprints and impacts with products such as low-impact tires. Studies and evaluations were conducted for the evaluation of several commonly used low-impact tires to help determine if the tires will be beneficial to groups such as LRAM and LCTA.

b. Laboratory Hard Surface, Soft Surface, and Plunger studies were conducted on three low-impact tires (Interco Trxus, Mickey Thompson BAHA Belted HP, Kevlar Dick Cepek F-C) and the results were compared with a standard, currently used military tire (Goodyear Wrangler MT). Laboratory tests include deflection, rutting, footprint, and plunger studies at pressures ranging from 10–30 psi and loads ranging from 600 to 2,000 lb. Differences were observed in tire performance (deflection, footprint area, rut depth, and conformability) relating to environmental impacts such as rutting and compaction, off-roading capabilities, and longevity of tire life.

c. Field tests were also conducted at Yuma Proving Grounds, AZ and Camp Atterbury, IN on three of the low-impact tires used in the laboratory tests, with a range of commonly used military vehicles. Field tests indicated that there were differences between tire performances. The field tests included the following:

i. Driving single tires over a plunger and measuring plunger depth to illustrate conformability of the tire.

ii. Driving the modified M1008 (CUCV) in a straight line at various tire pressures to determine rutting depth and distribution width.

iii. Driving the M1087A1 (HMMWV) in spirals to determine differences in rutting depth, disturbed width, soil compaction during various turning radii and speeds.

iv. Driving a modified M1008 (CUCV), M998 (HMMWV), and M1025 (HUMVEE) in spirals as with iii on vegetated areas. This included measurements of vegetative impacts.

d. Appendix A contains the introduction which explains the importance of the low-impact tire evaluation to the Army's environmental program. Results of this study do indicate a difference between tires, but it is necessary to obtain permission from the fleet manager to use alternative tires on government vehicles.

e. Appendix B provides the literature review process used for both laboratory and field studies.

f. Appendix C contains laboratory procedures and results for the following tests:

i. Hard Surface Test (Deflection & Footprint)
ii. Soft Surface Test (Rutting)
iii. Plunger Test.

g. Appendix D contains procedures and results for the following field tests:

i. Plunger Drive-Over Tests
ii. Rutting Tests
iii. Vehicle Spiral Tests in Sand
iv. Vehicle Spiral Tests Over Vegetation.

5. Points of contact. HQUSACE is the proponent for this document. The POC at HQUSACE is Malcolm E. McLeod, CEMP-II, 202-761-0632, or e-mail: malcolm.e.mcleod@usace.army.mil.

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FOR THE COMMANDER:

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Appendix A: Introduction

Under the Sikes Act, Army Regulation (AR) 200-3, Executive Order (EO) 13112, the Clean Air Act, and the Clean Water Act, installations are required to maintain a healthy, no net loss environment. As such, it is vital to determine when and where negative impacts on soil, water, plant and animal communities are occurring. This knowledge is gained through monitoring programs such as Land Condition Trend Analysis (LCTA).

Low Impact Environmentally Friendly (LIEF) tires could potentially allow natural resources personnel to limit vehicle impacts to installation lands during monitoring activities. LIEF tires, with the ability to conform to a hard surface and distribute the vehicle's weight more evenly, may cause less damage when driving over natural landscape. The U.S. Fish and Wildlife Service in Arizona is currently using LIEF tires and has experienced a significant reduction in blow outs and observed less track and rutting damage compared to standard off-road tires[*]. However, little quantitative information on the effect of LIEF tires on natural vegetation and soils is available.

Yuma Proving Ground (YPG), AZ, monitors sensitive sites as part of the installation's Integrated Training Area Management (ITAM) program. LCTA monitoring protocols have been implemented to monitor selected sites. LCTA monitoring plots are permanent plots that are periodically remeasured. Repeated access to these permanent measurement plots potentially results in vehicle impacts to areas that the installation is trying to protect from nontraining impacts. YPG limits access to some sensitive sites to 5-year intervals so as to limit potential LCTA vehicle impacts. This 5-year sampling interval is too infrequent for some habitats and species of interest, i.e., cryptogamic crusts or gopher tortoise (*Gopherus polyphemus)*. LIEF tires might reduce the impact of LCTA vehicle traffic in sensitive areas, thereby allowing a more frequent sampling schedule.

To evaluate the hypothesis that LIEF tires reduce vehicle-induced site impacts, a study was conducted to compare the potential impact of LIEF to the conventional tires used on the High-Mobility Multipurpose Wheeled Vehicle (HMMWV). Two sets of LIEF tires were tested in 2001 at YPG and Camp Atterbury, IN,

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[*] John Morgart, U.S. Fish and Wildlife Service, personal communication, 2003.

using a HMMWV. The locations are in very different areas or ecoregions. YPG is in Arizona where many highly sensitive and fragile habitats that support Threatened and Endangered Species (TES) require monitoring under the National Environmental Policy Act (NEPA) and AR 200-3. Also, soil moisture is usually very low, with annual precipitation of 2.94 inches per year. Camp Atterbury represents fairly resilient grassland and woodland habitats due to a higher rainfall amount (42 inches per year) and more fertile soils. The two areas allow LIEF tires to be evaluated at sites with diverse characteristics.

During field testing, observational evaluations indicated that the LIEF tires caused fewer site impacts. The observational data agreed with YPG, Arizona Boarder Patrol, and Arizona Fish and Wildlife Survey personnel observations. All organizations noticed less vegetation damage and decreased tire rutting. The LIEF tires had additional benefits of increased riding comfort (conformability) and reduced incidence of flat tires. These additional benefits appear to be the result of the tire’s ability to conform to soil surface features. Both laboratory and field analysis indicated statistically significant differences (Appendix C & D) between the conventional and LIEF tires. However, biologically meaningful differences in tire impacts could not be verified from the studies.

Written permission from fleet managers must be obtained for government vehicles before purchasing and installing tires other than outlined in the General Services Administration (GSA) schedule. When installing and using tires, follow manufacture instructions, specifically for paved and nonpaved driving surface optimal tire pressures.

Appendix B: Review of Literature

Tires differ in their potential environmental impacts based on tire carcass stiffness, lug size and locations, and tire size. Changes in these parameters as well as tire load and inflation pressure can affect tire-terrain impacts.

Research on tire impact of soil and vegetation has been conducted in a variety of aspects. Carrow (1989) studied turfgrass wear affected by golf cart tire design and traffic patterns. He assessed the wear damage by visual turf quality, color, verdure and leaf bruising. Three traffic patterns — semi-circular, sharp turn, and straight-line — were discussed in his paper. His study shows that differences in wear injury between the tire designs did occur, but were minor in most instances. Traffic distribution and sharpness of turns is more important than type of car or tire design in minimizing wear of golf course turf.

Another turf damage study was conducted by Arthur (1996). He researched the influence of turf tire sipe density on turf damage. Different from the damage measurement method used by Carrow, Arthur's method used six turf leaves to examine their damage severity after each test. Damage was recorded as a percentage of the actual blade area, but Arthur did not find any statistical conclusion regarding turf damage.

A study of soil compaction on a heavy clay states that soil compaction of a single pass of a manure spreader was confined in the depth from 0 to 250 mm, which is within the tilled layer (Bedard et al. 1997). Bedard measured both soil dry bulk density and cone index (CI) to evaluate compaction. If the weight of spread was added to 154 kN, representative of a full load, soil compaction could exceed the depth of the tilled layer.

The peak soil-tire interface stresses on the lug, lug being defined as the portion of the tire that extends into the soil for the purpose of developing traction (ASAE S296.4), of a tire can be affected by both dynamic load and inflation pressure (Raper 1994). Raper developed a finite element model and then used the peak soil-tire interface stresses to examine the depth and degree of predicted soil stresses. He suggested that, to limit soil compaction, both dynamic load and tire inflation pressure should be optimized.

As soil moisture increases up to saturation, soils typically become more compressible and susceptible to soil compaction. Soil compaction increases density, thus decreasing root penetration and hydraulic conductivity. In order to reduce excessive subsurface soil compaction, the dynamic load needs to be reduced as the subsurface moisture increases. Excessive surface soil compaction can be avoided by reducing the tire pressure in moist conditions. The optimal amount of dynamic load and tire pressure reduction needed is determined by the constitutive soil properties (compressibility).

Gill and Vandenberg (1962) evaluated the effect of inflation pressure on the pressure distribution of the tire footprint. Lower tire pressures generated lower tire footprint pressures and a larger contact area, so the tire contact width increased with lower tire pressures.

Sohne (1958) evaluated tire weights and pressures on theoretical subsurface stress distribution. At the same pressure, but with higher weights (loads), larger and deeper subsurface stresses were generated. Increasing the tire pressure increased the soil surface pressures.

The effect of tire inflation pressure on the tire vertical stiffness was investigated by Kising and Gohlich (1989). Higher inflation pressures and larger tires generated higher tire stiffness.

Lines and Murphy (1991) determined the variation of vertical damping rate for five different off-road tires. Damping coefficients varied threefold for the different tires because of tire carcass configurations.

Appendix C: Laboratory Tests

The University of Tennessee Biosystems Engineering and Environmental Sciences Department conducted laboratory tests on four different tires to determine deflection characteristics, rutting potential, and tire conformity. Deflection characteristics were obtained through hard surface tests, which measured deflection at various pressures. The results from the soft surface tests conducted on a constant simulated soil material (polyethylene) were used to describe the sinkage or rutting potential for each tire. Finally, tire conformity was determined through the plunger tests in which each tire was pushed down over a standard size plunger. For each test, the tire pressure ranged from 10 to 30 psi and the applied loads ranged from 600 to 2,000 lb. Tire footprint area was determined in the deflection tests by measuring the width and length of tire contact area.

Tires Tested

The tires tested are shown below. Note the different maximum pressure and load for each tire, indicating possible different operating conditions for the tire when mounted on the vehicles.

Tire — Interco Trxus
- Size - 33 x 13.50 - 16 LT
- Maximum Load - 2,800 lb
- Maximum Pressure - 45 psi
- Load Range - D
- Ply Rating - NA
- Tread Ply - 6-ply polyester
- Sidewall Ply - 4-ply polyester

Tire — Mickey Thompson BAHA Belted HP
Size - 33 x 12.50 - 16 LT
Maximum Load - 2,755 lb
Maximum Pressure - 45 psi
Load Range - D
Ply Rating - NA
Tread Ply - 4-ply poly + 2-ply fiberglass belts
Sidewall Ply - 4-ply poly

Tire — Kevlar Dick Cepek F-C
Size - 38 x 15.50 - 16.5 LT
Maximum Load - 3,275 lb
Maximum Pressure - 30 psi
Load Range - C
Ply Rating - A
Tread Ply - 4-ply poly + 2 ply Kevlar
Sidewall Ply - 4-ply poly cord

Tire — Goodyear Wrangler MT (Standard Military Tire)
Size 37 X 12.5 - 16.5 LT
Maximum Load - 3,850 lb
Maximum Pressure - 50 psi
Ply Rating - 6
Tread Ply - 4-ply (2 poly and 2 steel)
Sidewall Ply - 2-ply poly cord

Hard Surface Test

Each of the four tires was tested to measure deflection and footprint area at 600–2,000 lb in 200-lb increments at pressures ranging from 10 to 30 psi in 5-psi increments. The pressures were measured with an Intercomp electronic pressure gage (InterComp, Inc., Lauderdale By the Sea, FL). The tire was placed on the Intercomp Tire Tester with a one-quarter-inch thick 18 x 18-inch steel plate for the contact surface (Figure C1). The plate was marked with a grid to measure the footprint area.

Figure C1. Hard surface test.

The following test procedure, as recommended by Intercomp, was conducted. The load cell was zeroed with no contact with the tire. The jack was moved up until there was a 10-lb load on the tire and the electronic ruler was zeroed. The jack was then moved up one-tenth of an inch and allowed to settle for 3 minutes. The jack was again moved up until a 600-lb load was on the tire. A footprint and deflection measurement was made. The deflection was measured using the electronic ruler on the tire tester. The footprint was measured by placing a thin plastic ruler as far under the tire as it would go. The length and width were then read from the grid on the steel plate.

After the measurements were made, the jack was moved up to increase the load by 200 lb. Deflection and footprint measurements were then repeated on the tire. After measurements were made up to 2,000 lb, the load was released, the tire pressure was adjusted, and the process was repeated for another tire.

The footprint area was assumed to be an ellipse (Figure C2), and the area was calculated using the formula:

$$\text{Area (A)} = \text{Length (L)} * \text{Width (W)} * 0.78$$

The data were analyzed by plotting the footprint area and deflection versus load for each tire at the different pressures. The tires were compared also by plotting the footprint area and deflection load with the pressure constant.

Generally, the tire deflection increased with increasing load and decreasing tire pressure for all of the tires (Figures C3 through C6).

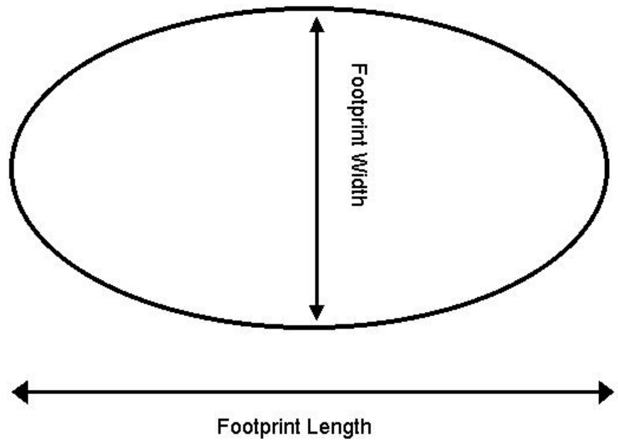

Figure C2. Diagram of measured tire footprint area.

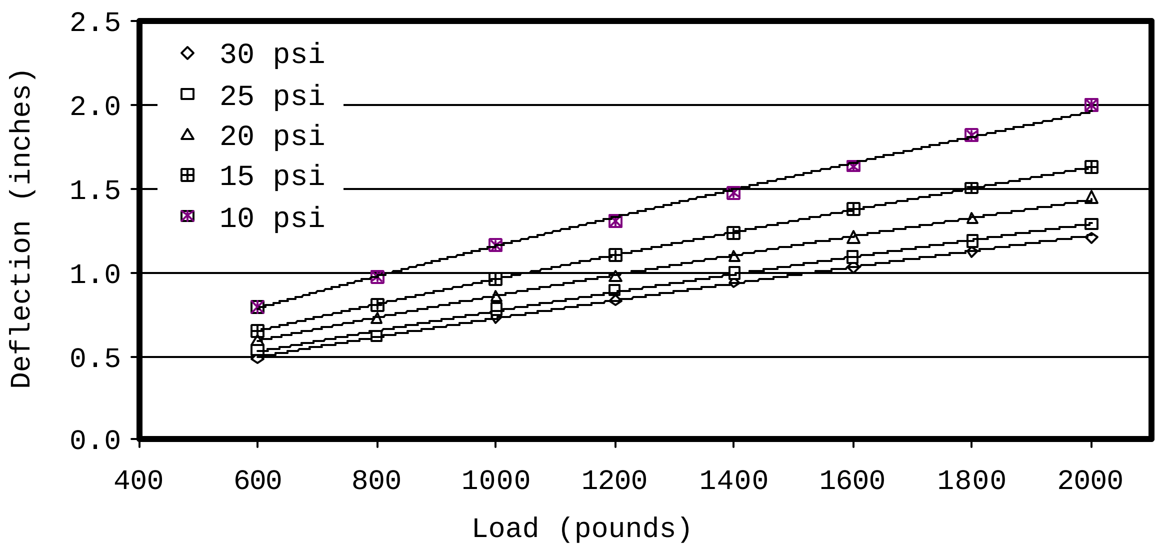

Figure C3. Baha tire deflection.

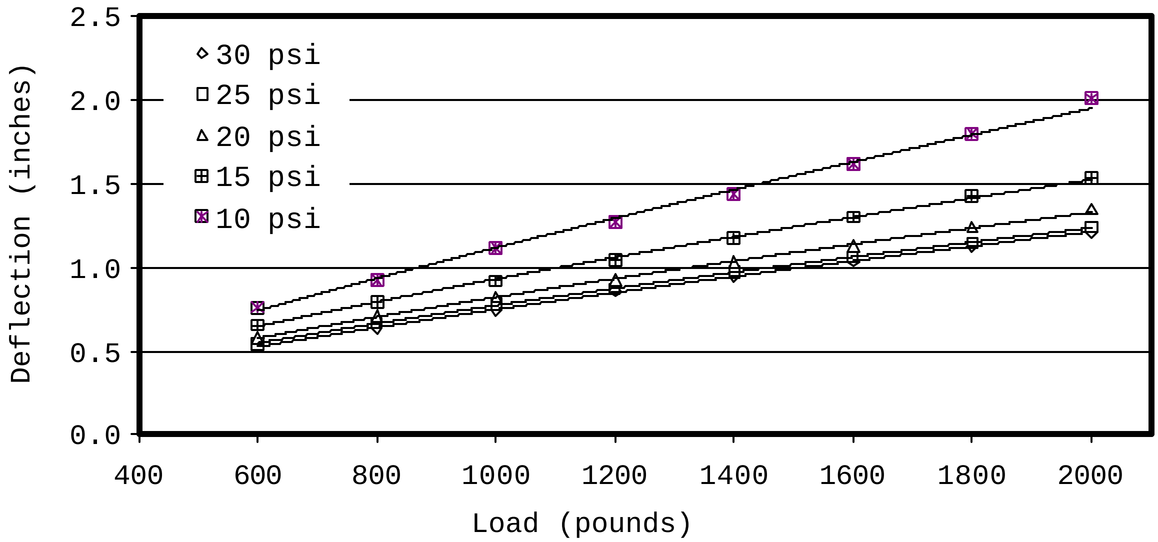

Figure C4. Kevlar tire deflection.

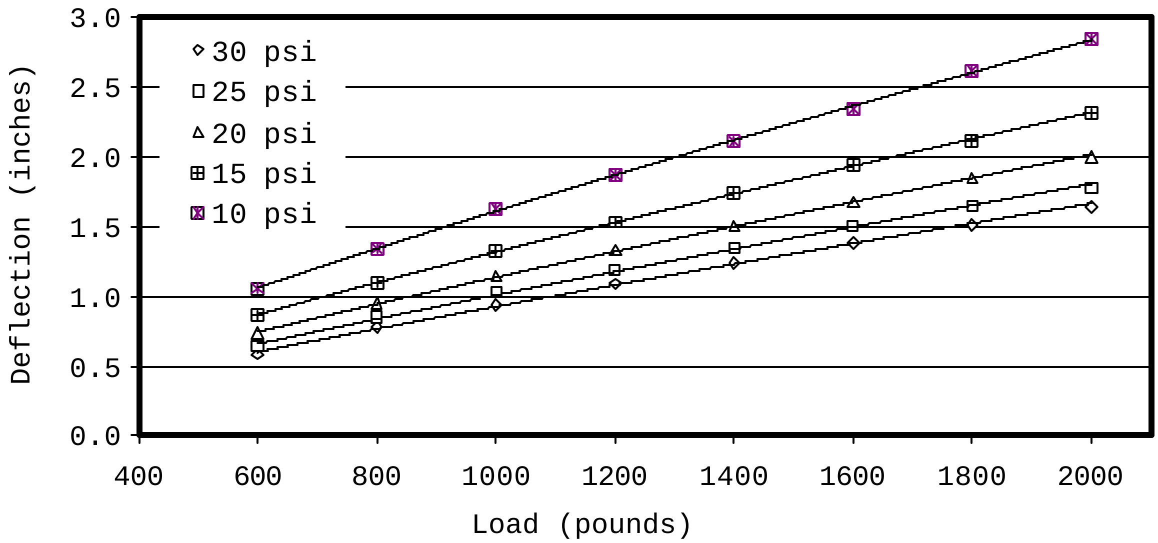

Figure C5. Wrangler tire deflection.

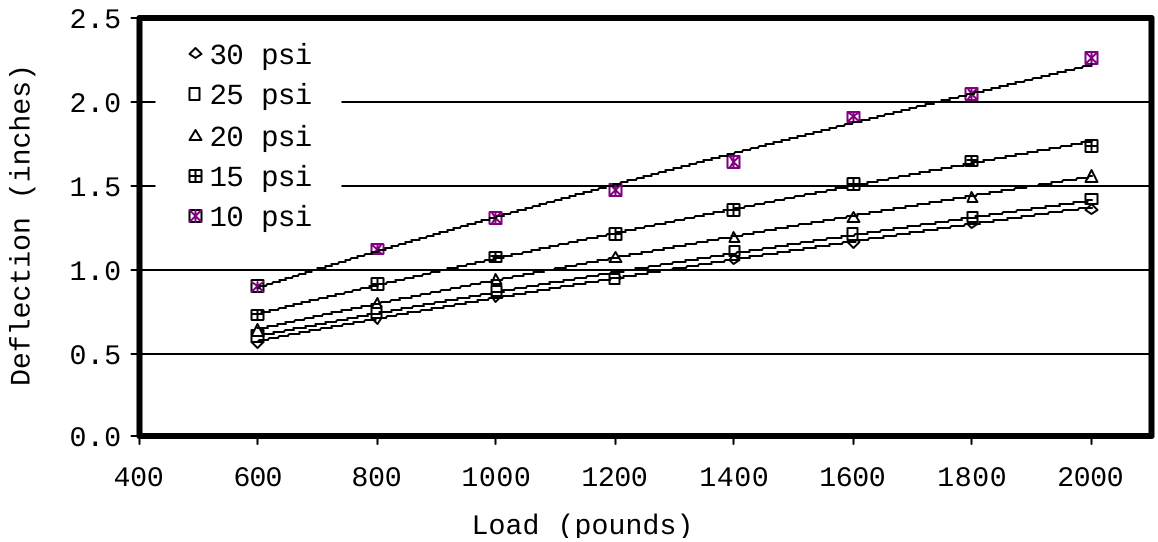

Figure C6. Trxus tire deflection.

Comparing all of the tires at a single pressure, it was noted that the Wrangler, a radial tire, exhibited the highest tire deflection, followed by the Trxus, for all test pressures. The Kevlar and Baha tires exhibited the lowest deflections (Figures C7 through C11). Higher tire deflections indicates a possible weaker side wall (2 ply compared to 4 ply). However, weaker sidewalls do not necessarily influence terrain impacts.

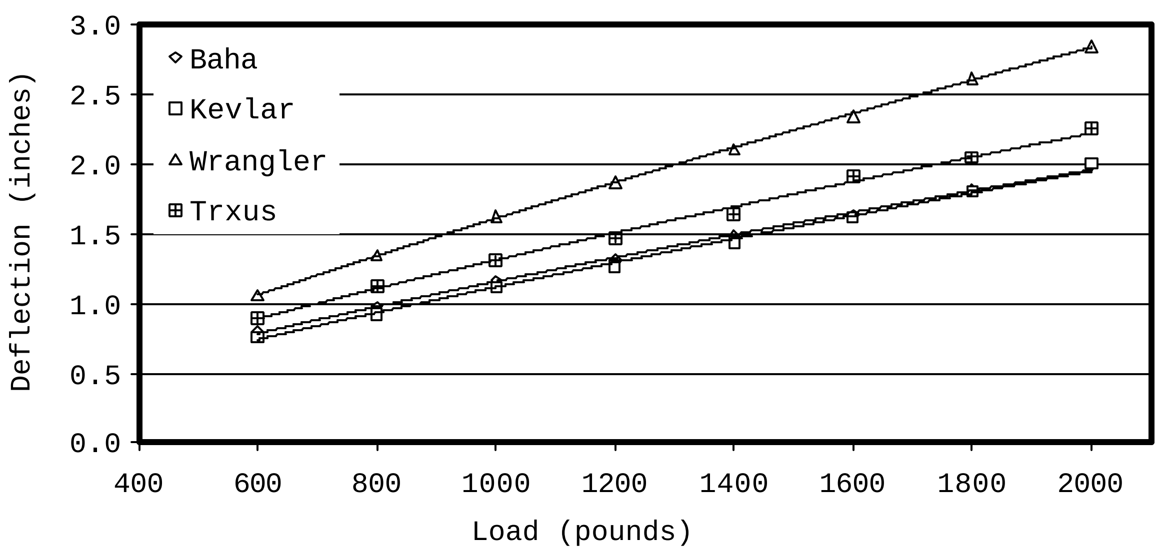

Figure C7. Tire deflection at 10 psi.

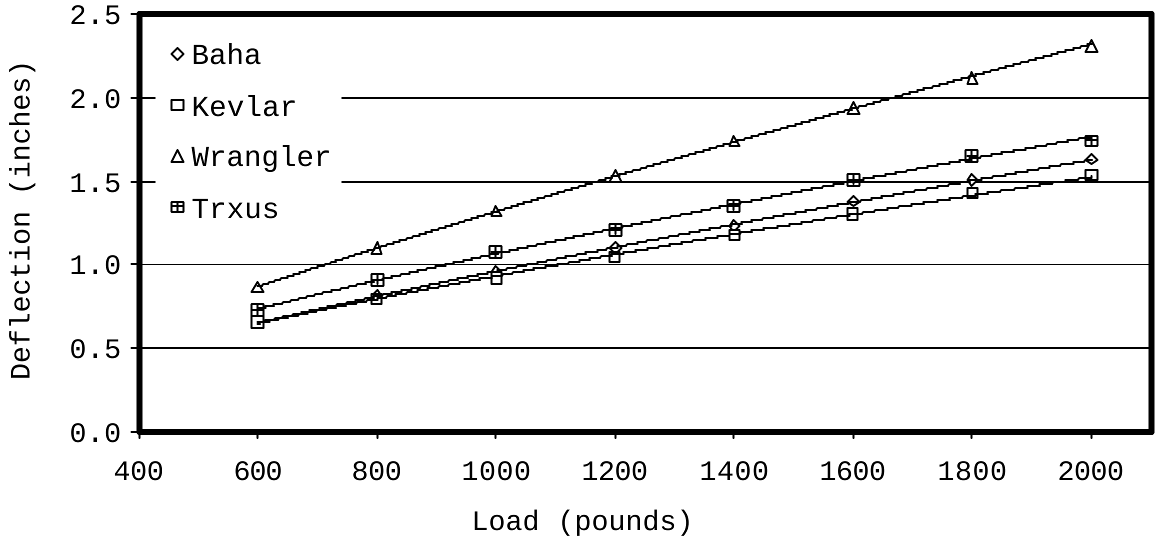

Figure C8. Tire deflection at 15 psi.

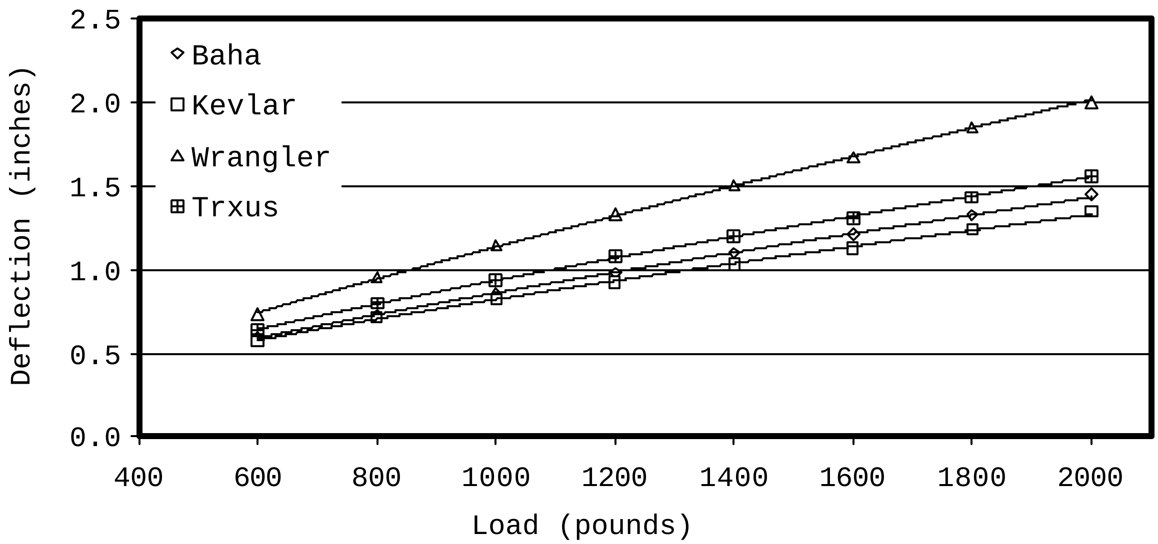

Figure C9. Tire deflection at 20 psi.

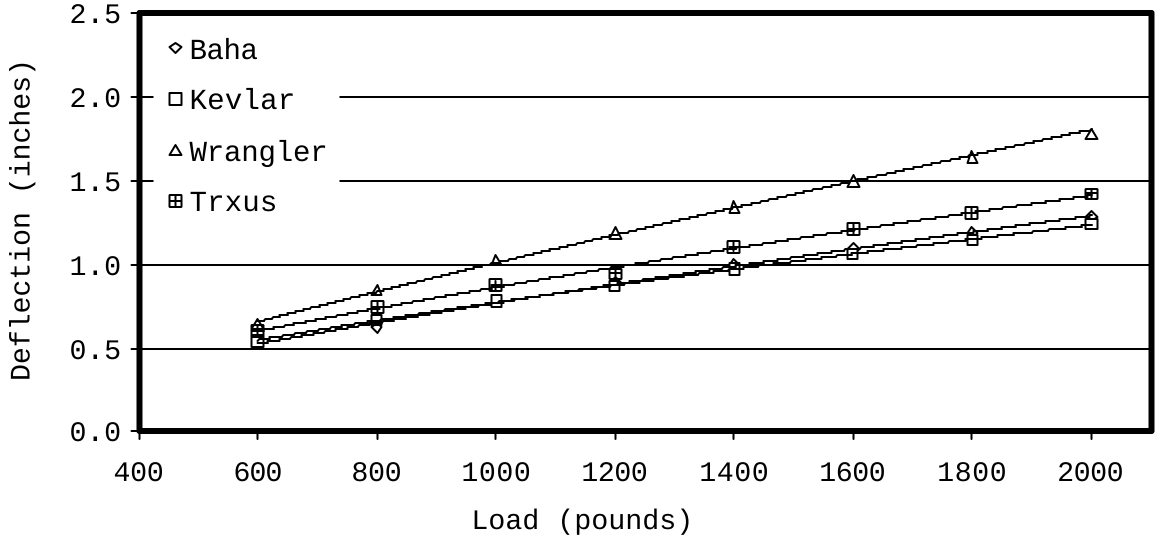

Figure C10. Tire deflection at 25 psi.

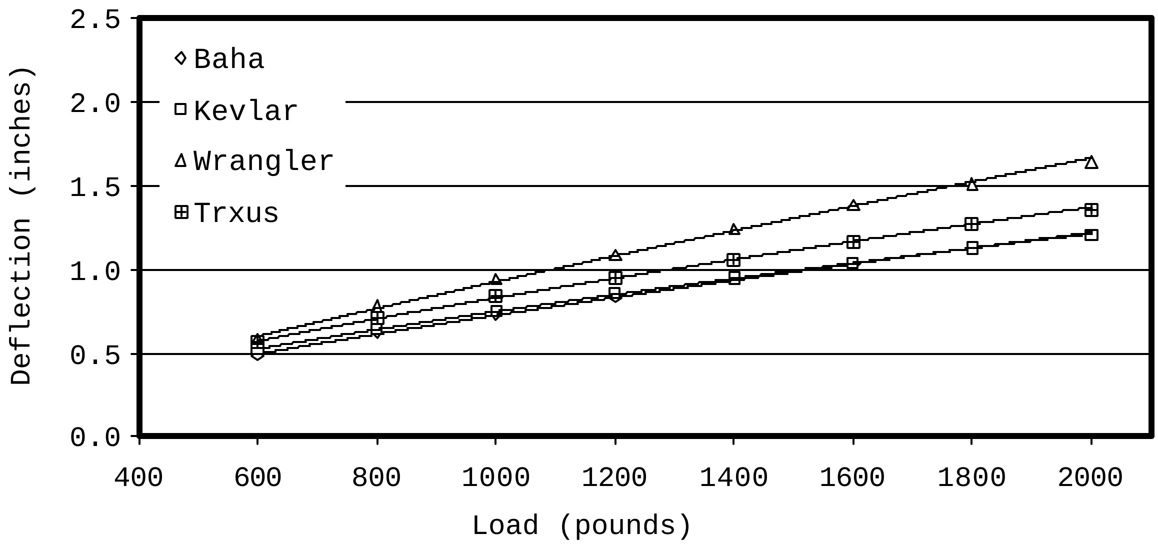

Figure C11. Tire deflection at 30 psi.

As with the deflection results, the footprint area for each tire also increased with increasing loads and decreasing tire pressure (Figures C12 through C15).

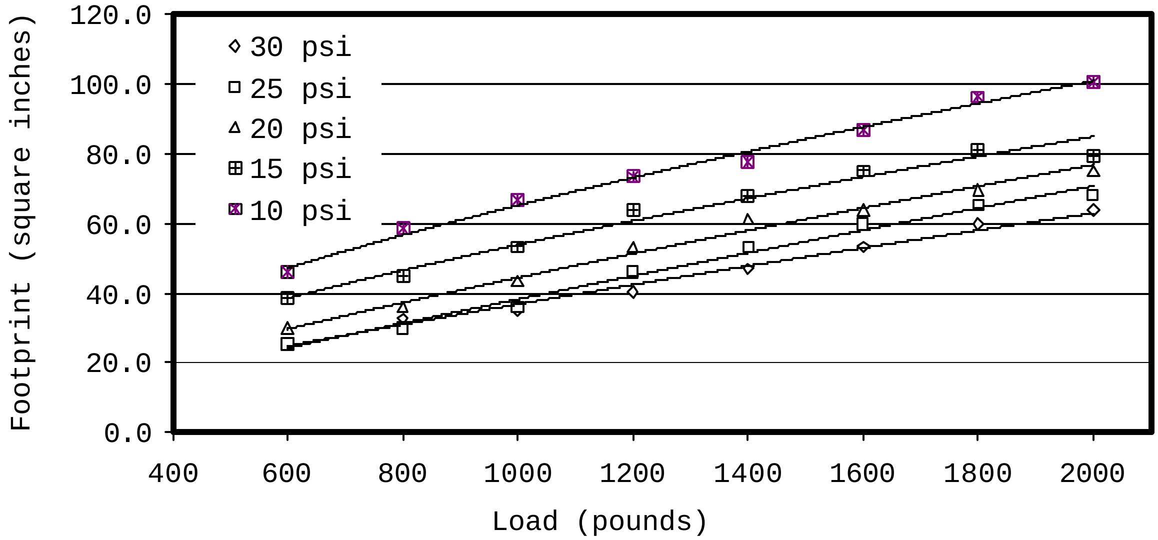

Figure C12. Baha tire footprint.

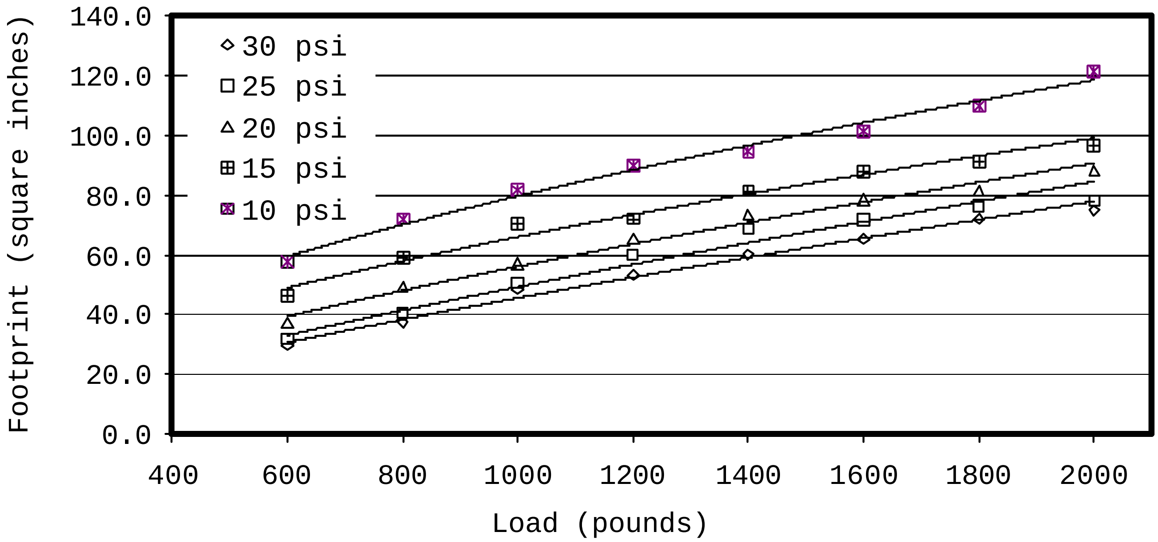

Figure C13. Kevlar tire footprint.

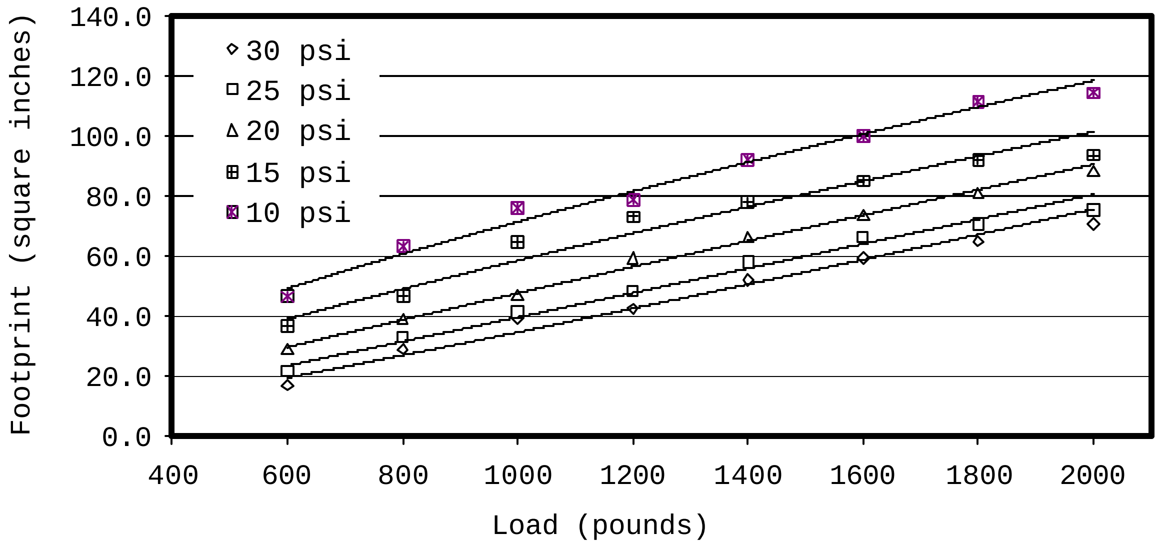

Figure C14. Wrangler tire footprint.

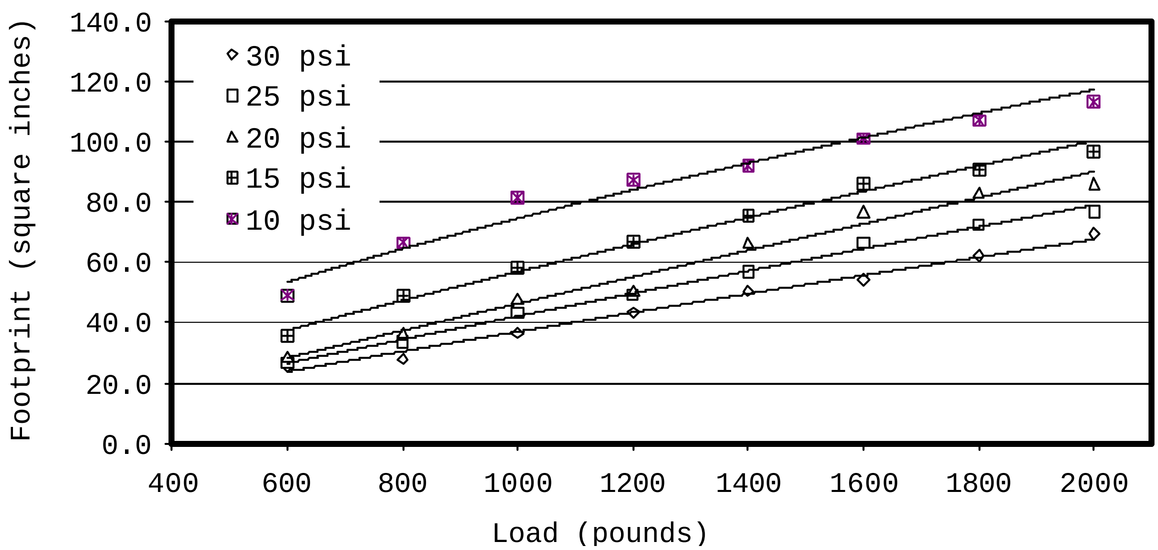

Figure C15. Trxus tire footprint.

By comparing all of the tires at singular pressures (Figures C16 through C20), the Kevlar tire exhibited the largest footprint, but this finding was less pronounced at lower tire pressures. The Baha tire exhibited the smallest footprint, although less pronounced at higher tire pressures. Large footprint areas indicate higher amounts of terrain impacted, but generally lower average soil surface stresses.

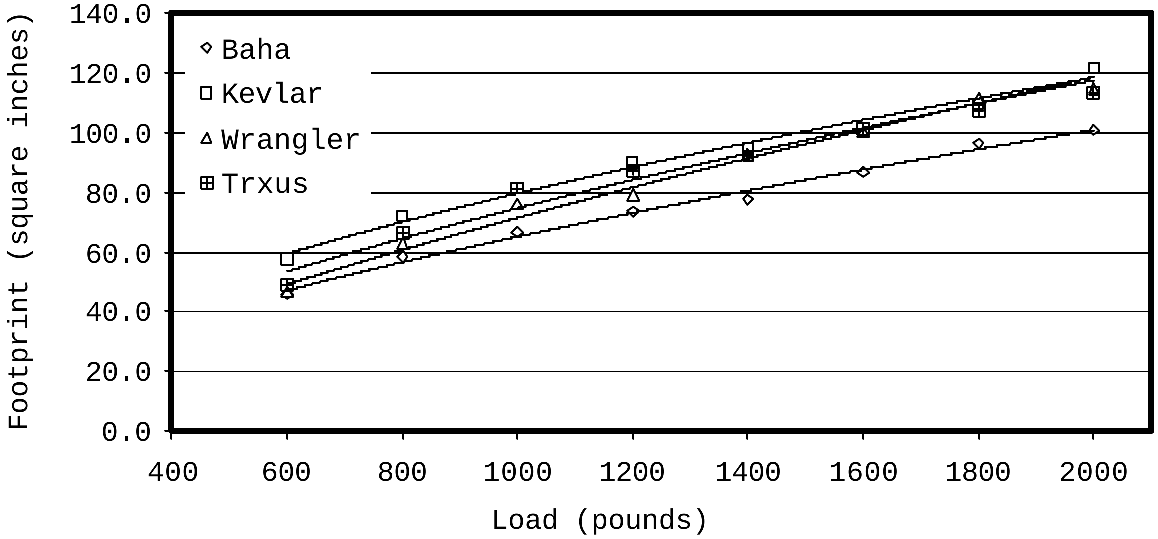

Figure C16. Tire footprint at 10 psi.

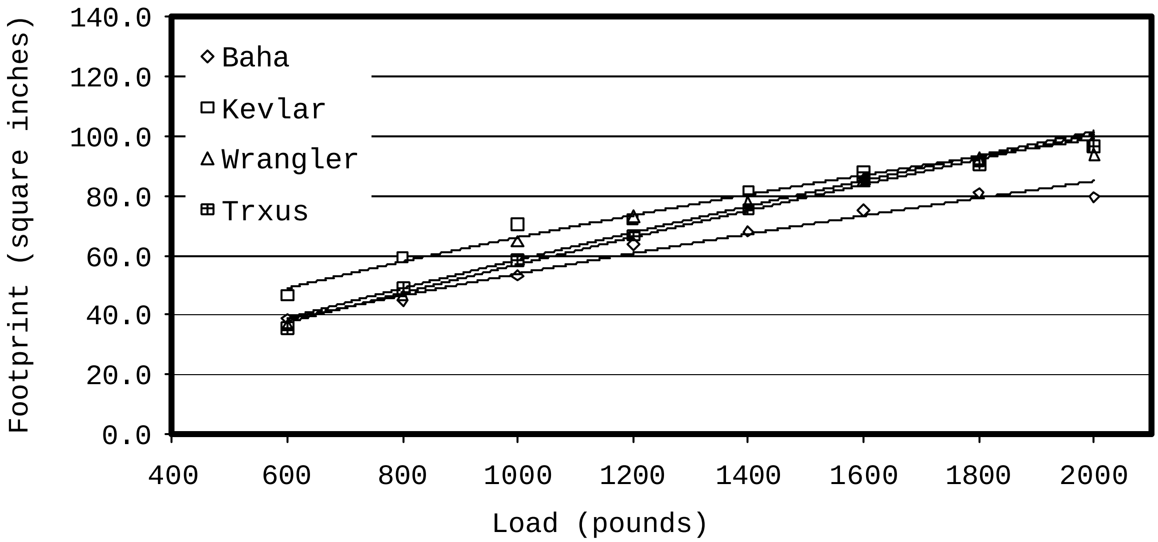

Figure C17. Tire footprint at 15 psi.

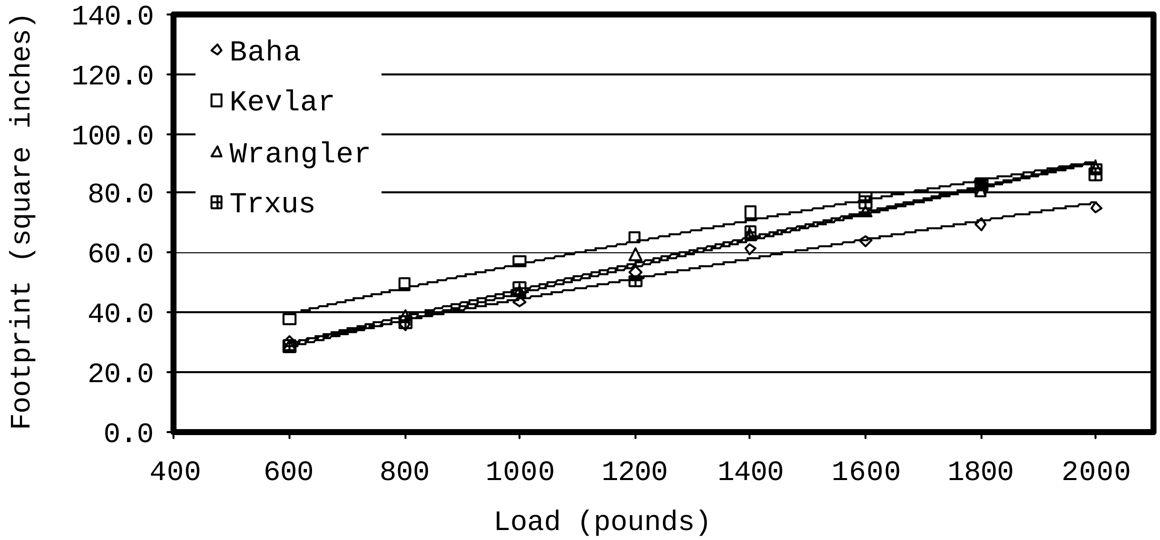

Figure C18. Tire footprint at 20 psi.

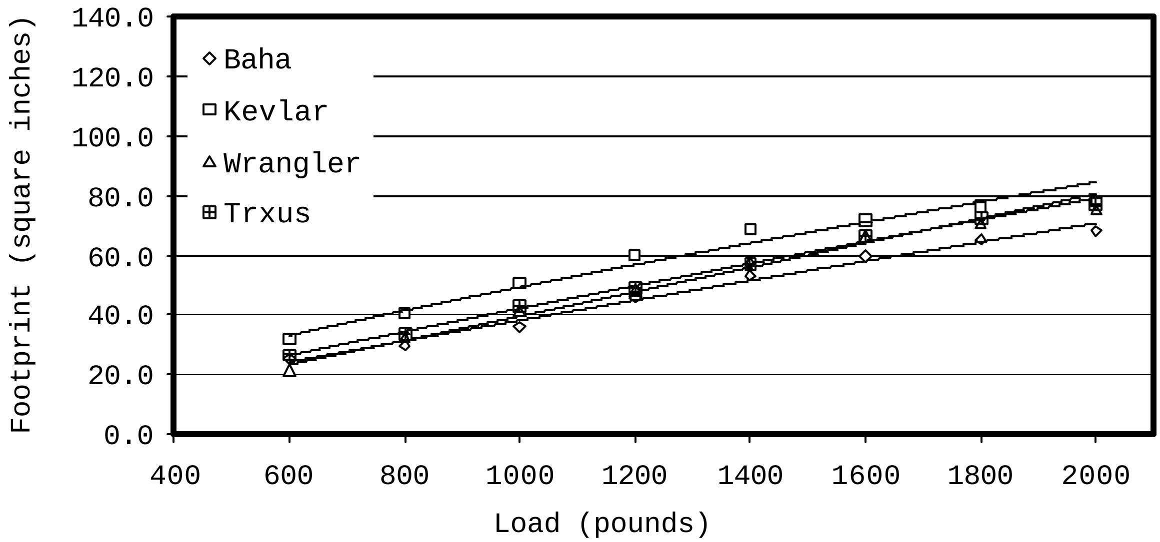

Figure C19. Tire footprint at 25 psi.

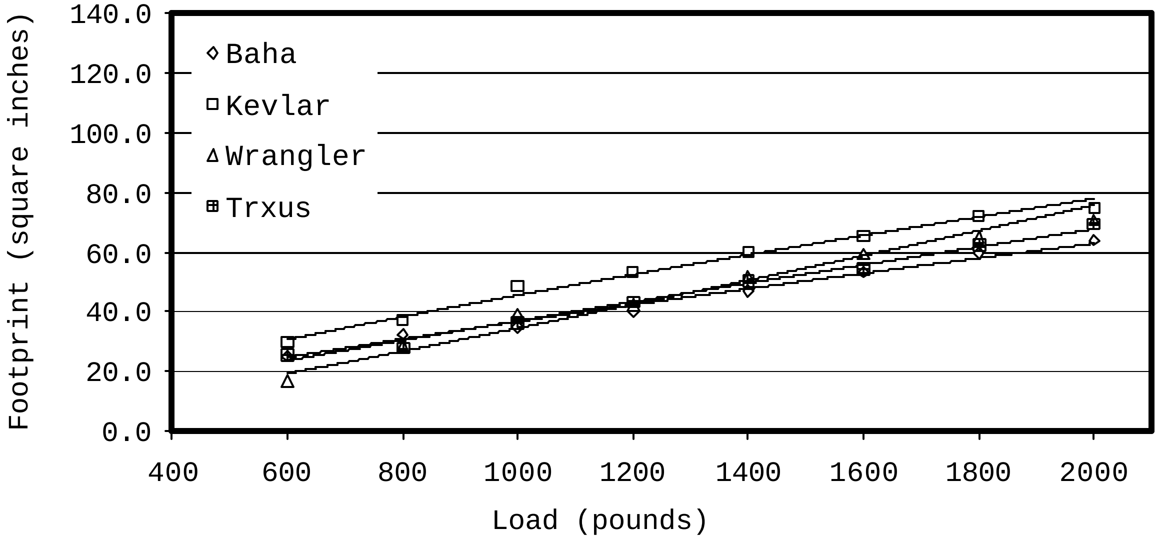

Figure C20. Tire footprint at 30 psi.

Soft Surface Test

Each of the four tires was tested to measure deflection on a soft surface at 600 to 2,000 lb in 200-lb increments at pressures ranging from 10 to 30 psi in 5-psi increments. The procedure used was the same as for the hard surface test except the tire was placed on the Intercomp Tire Tester with an 8-inch thick 12 x 12-inch polyethylene foam pad for the contact surface to simulate soil (shown in Figure C21).

Figure C21. Soft surface test.

The deflection measured in the soft surface test is the total deflection, including the deflection of the tire and the foam. The total deflection was plotted versus load for each tire at the different pressures and for the different tires at the same pressure. The foam deflection was found by subtracting the tire deflection (found in the hard surface test) from the total deflection. This foam deflection was plotted versus load for each tire at the different pressures and for the different tires at the same pressure. Foam deflection is an indicator of the tire sinkage or rutting potential.

Similar tire sinkage/rutting characteristics were shown by all four tires (Figures C22 through C30). Tire rut depths generally increased with increasing tire pressure, although least obvious with the Kevlar tire. At the high pressures, 25–30 psi, the Kevlar tire, being the widest of the four tires, exhibited lowest rut depth compared to the other tires.

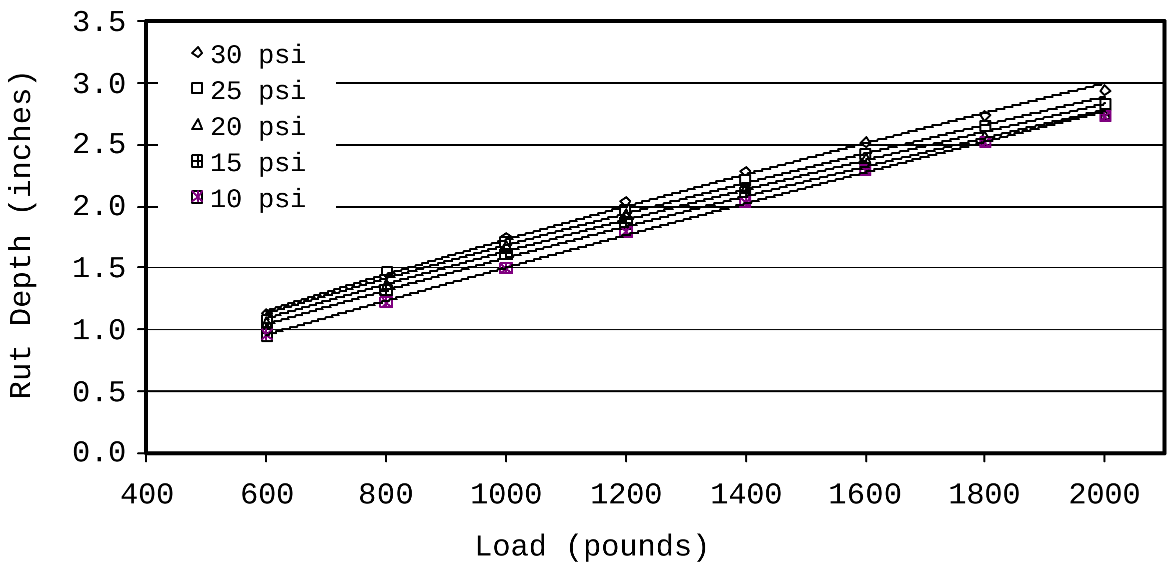

Figure C22. Baha tire rut depth.

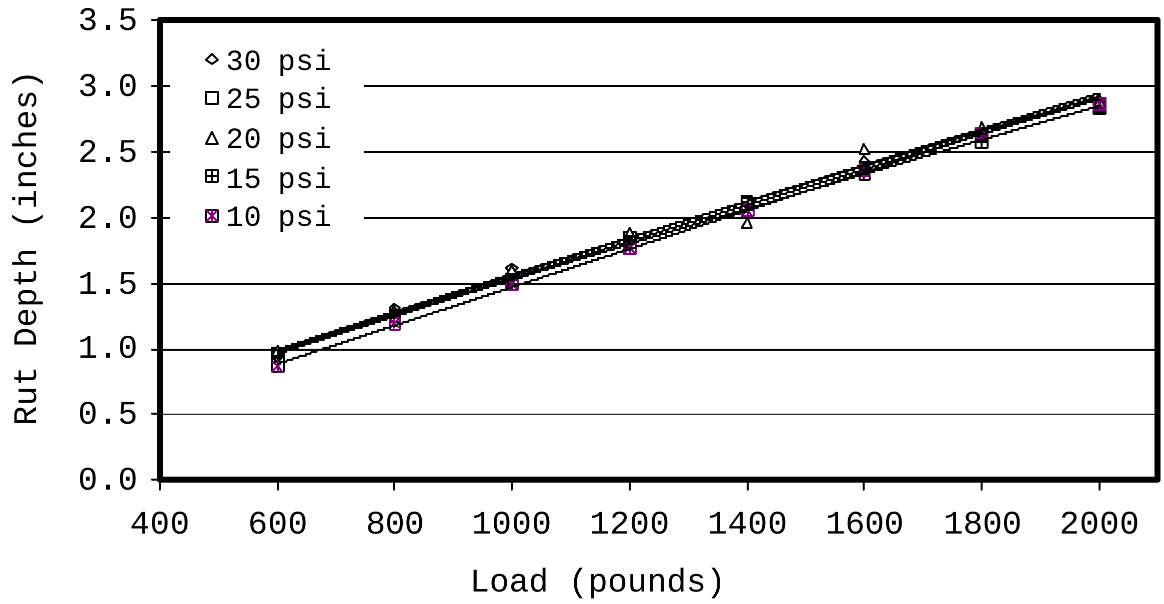

Figure C23. Kevlar tire rut depth.

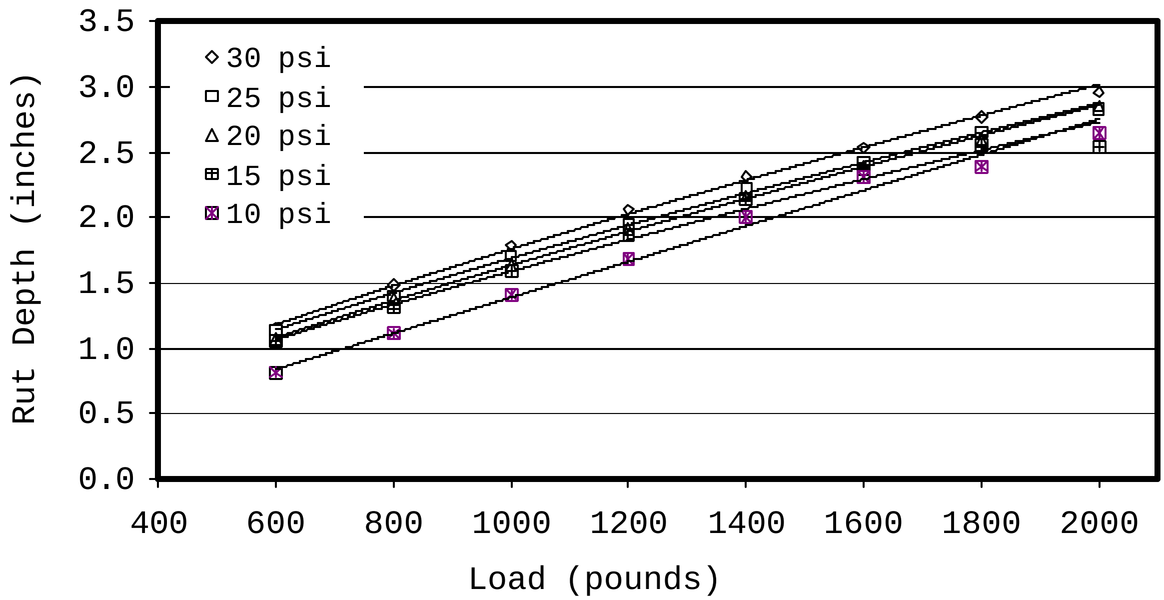

Figure C24. Wrangler tire rut depth.

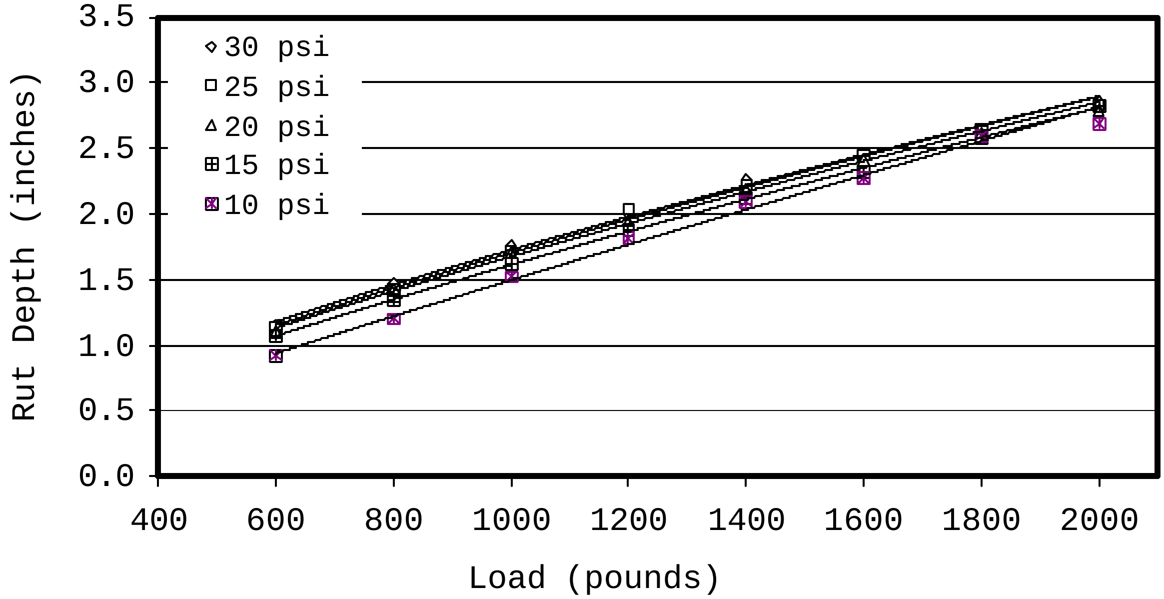

Figure C25. Trxus tire rut depth.

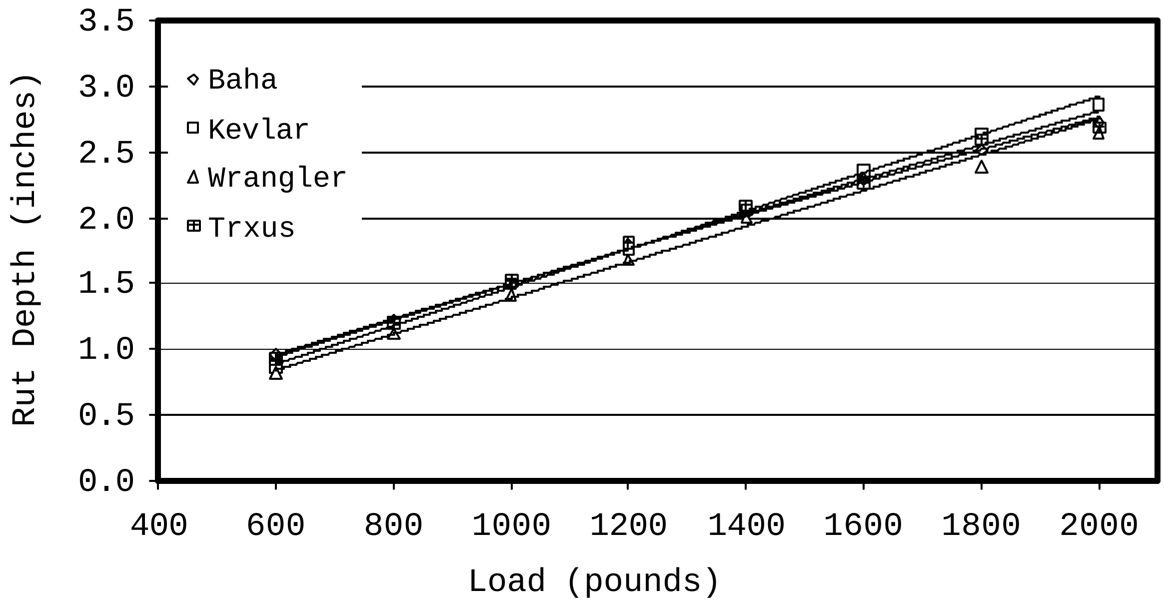

Figure C26. Rut depth at 10 psi.

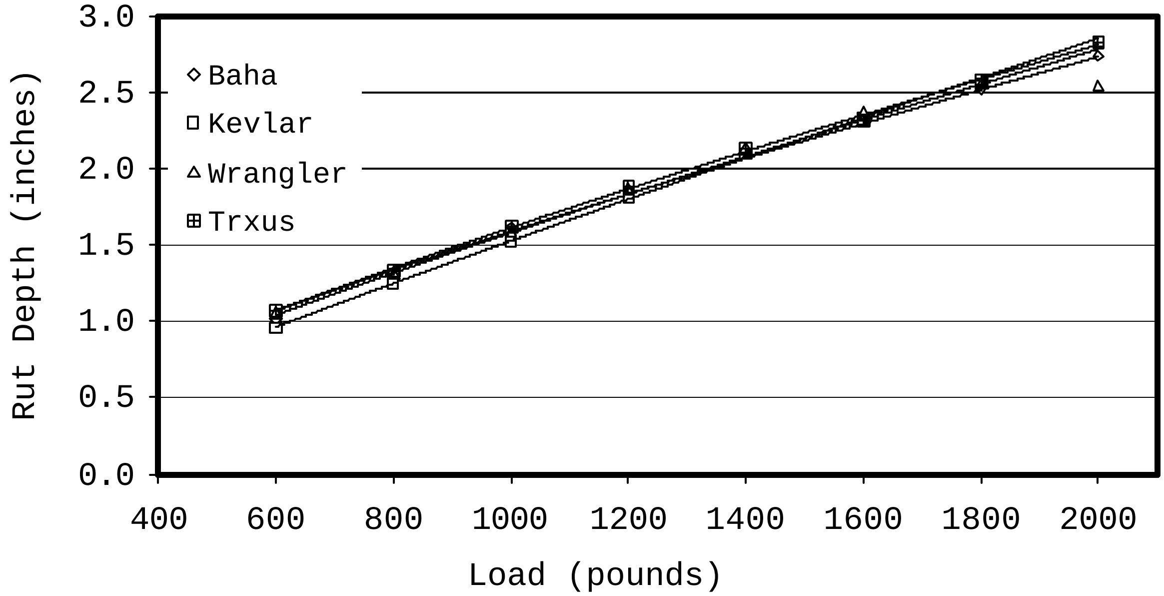

Figure C27. Rut depth at 15 psi.

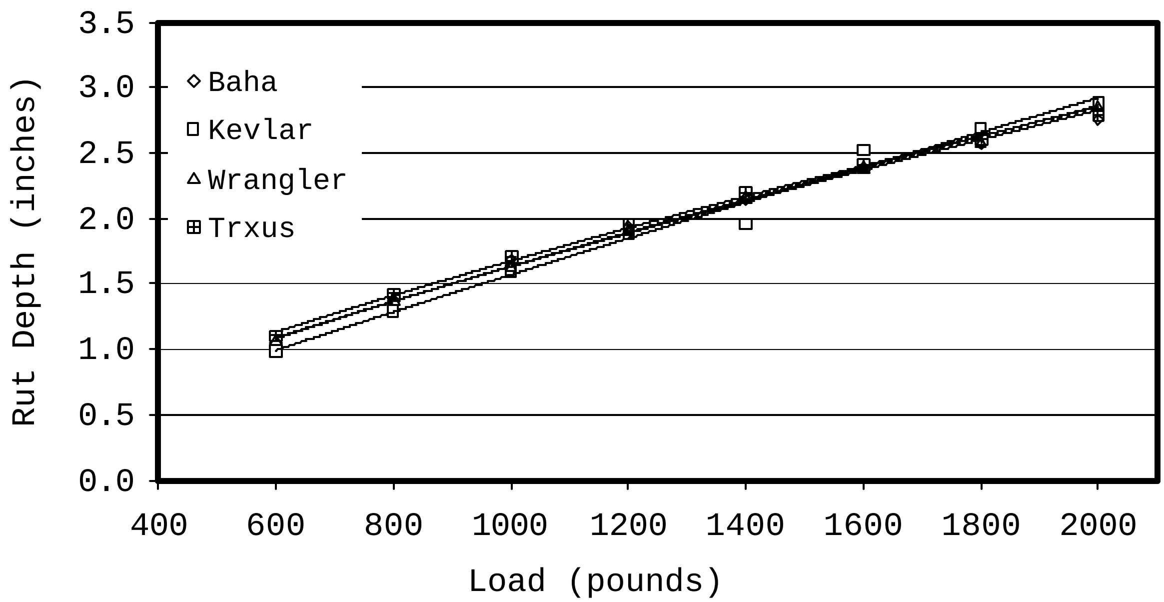

Figure C28. Rut depth at 20 psi.

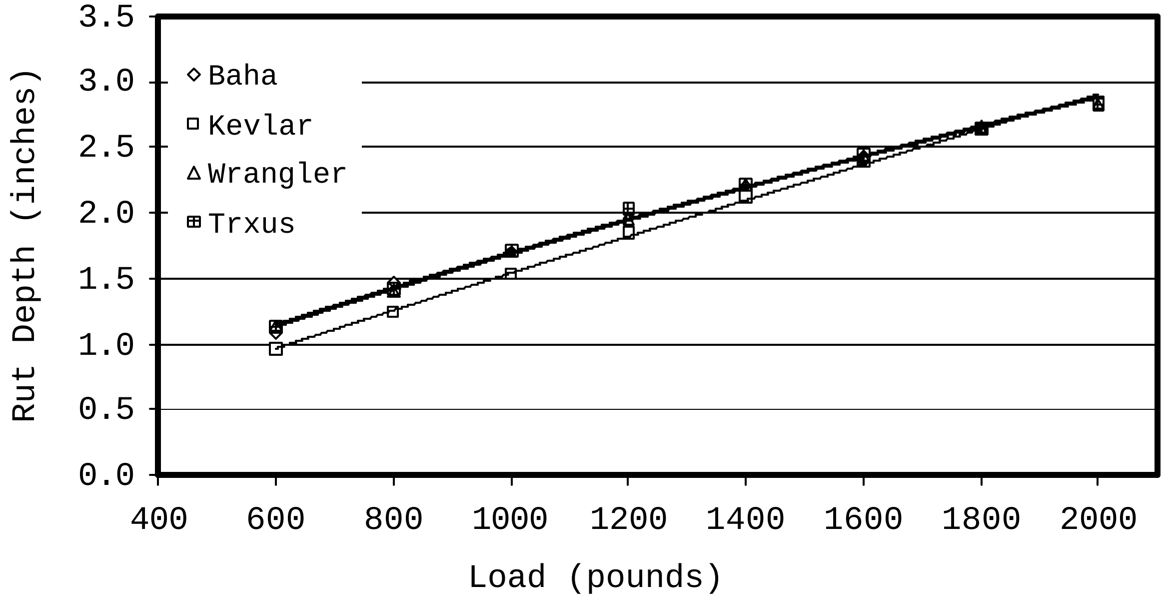

Figure C29. Rut depth at 25 psi.

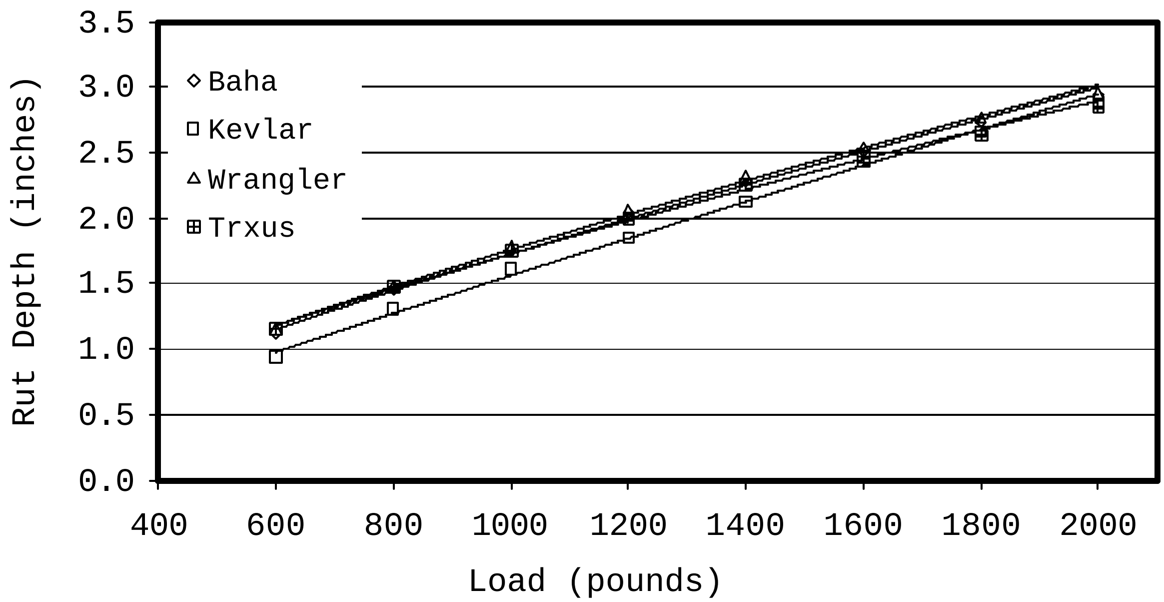

Figure C30. Rut depth at 30 psi.

Plunger Test

Each of the four tires was tested to measure the conformability of the tire over an object at 600 to 2,000 lb in 200-lb increments at pressures ranging from 10 to 30 psi in 5-psi increments. Each tire was placed on the Intercomp Tire Tester with a steel plunger for the contact surface. The plunger was 4.5 inches in total height, 3 inches in diameter, and the top was a hemisphere with a radius of 1.5 inches as shown in Figure C31.

Figure C31. Plunger test.

The load cell was zeroed with no contact with the tire. The jack was moved up until there was a 10-lb load on the tire and the electronic ruler was zeroed. The jack was then moved up one-tenth of an inch and allowed to settle for 3 minutes. The jack was moved up until the load on the tire was 600 lb. A deflection measurement was made using the electronic ruler. The jack was moved up to increase the load by 200 lb. After measurements were made up to 2,000 lb, the load was released, the tire pressure was adjusted, and the process was repeated on the other tires. The tire deflection onto the plunger was plotted versus load for each tire at the different pressures and for the different tires at the same pressure.

Generally, plunger deflection increased with increasing load and decreasing tire pressure (Figures C32 through C40). The Trxus tire exhibited the highest tire plunger deflection, and the Kevlar tire exhibited the lowest tire plunger deflections.

Higher tire plunger deflection indicates the ability of the tire to conform or engulf an obstacle. Higher conformability indicates more tire tread on the terrain as the vehicle passes over an object, producing less downward force on the obstacle.

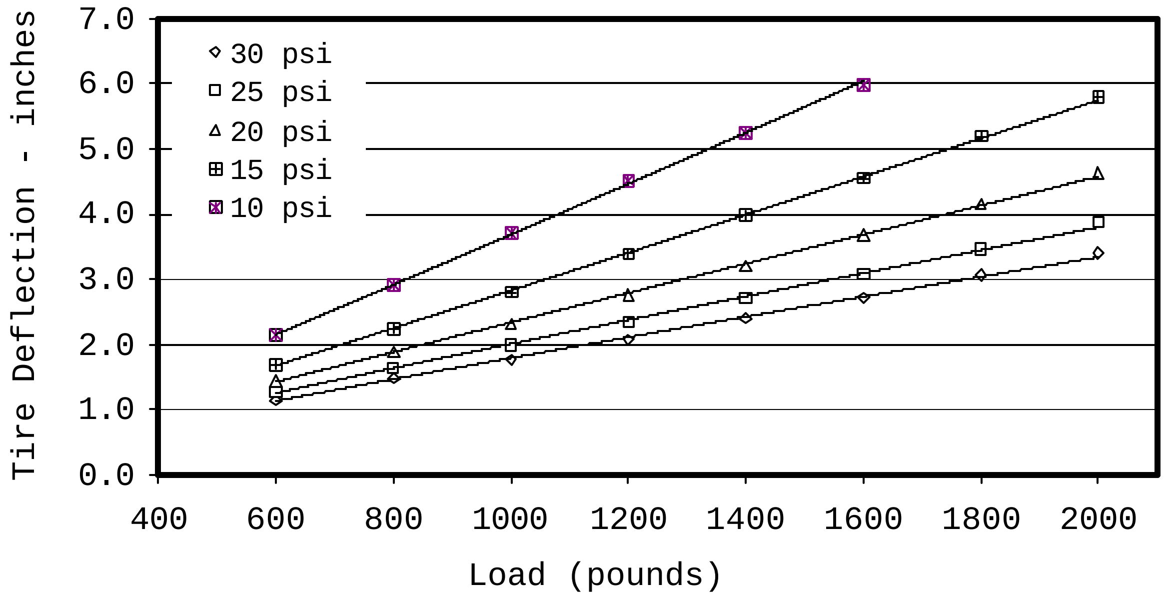

Figure C32. Baha tire plunger deflection.

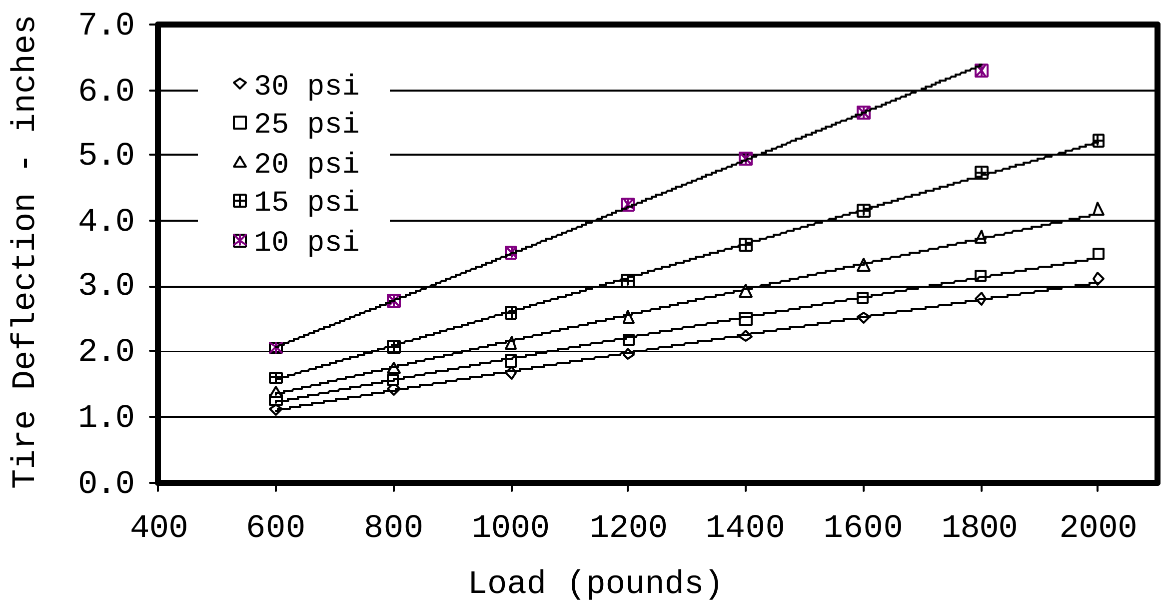

Figure C33. Kevlar plunger deflection.

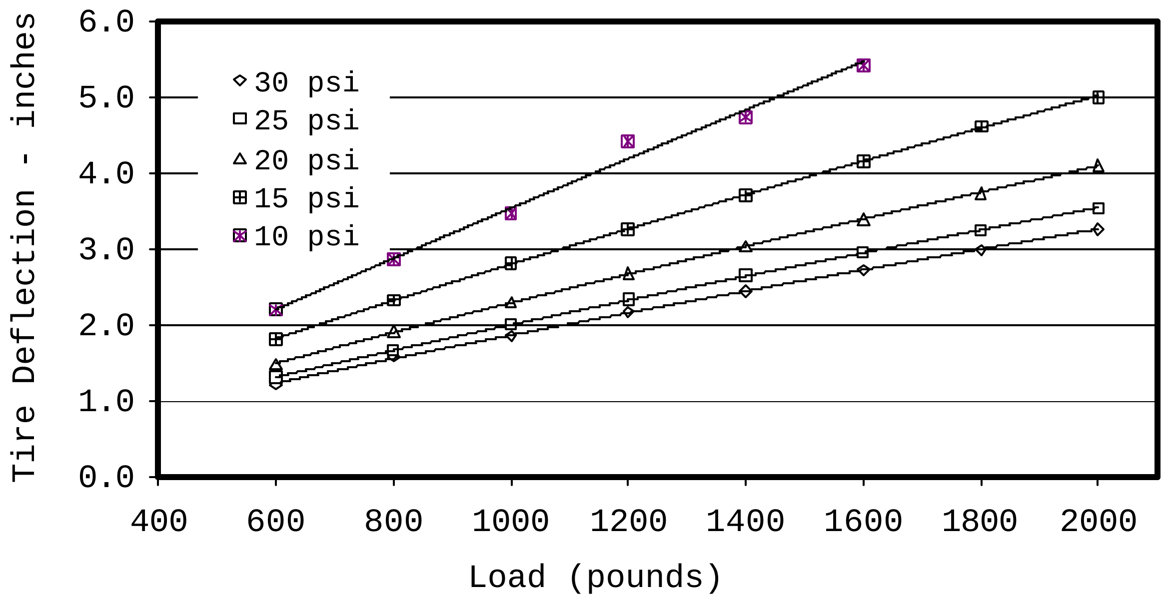

Figure C34. Wrangler tire plunger deflection.

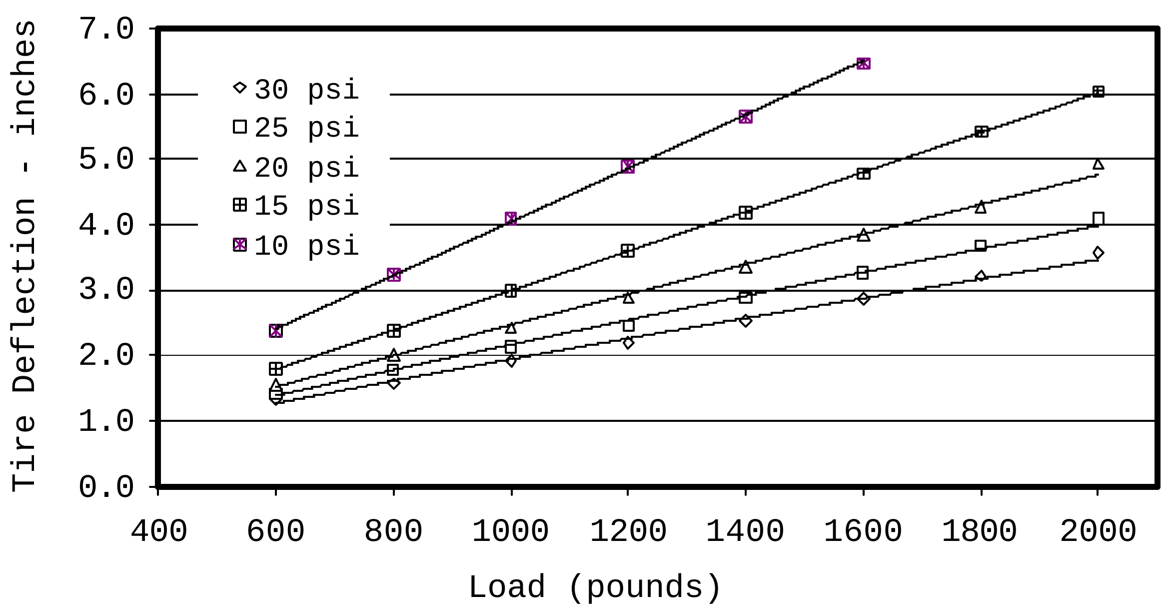

Figure C35. Trxus tire plunger deflection.

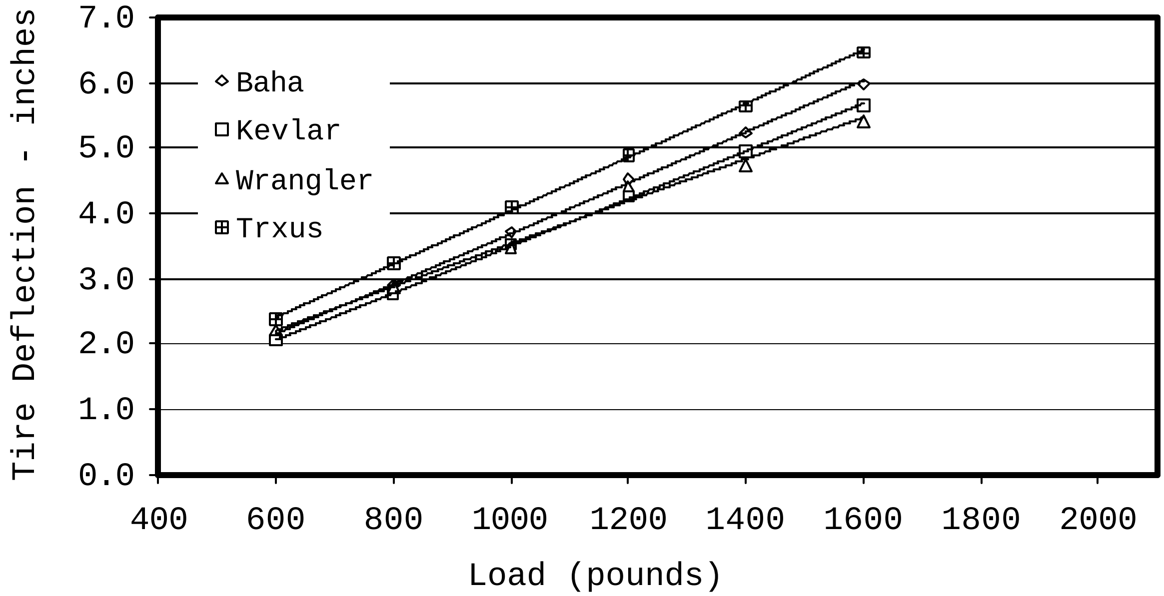

Figure C36. Plunger deflection at 10 psi.

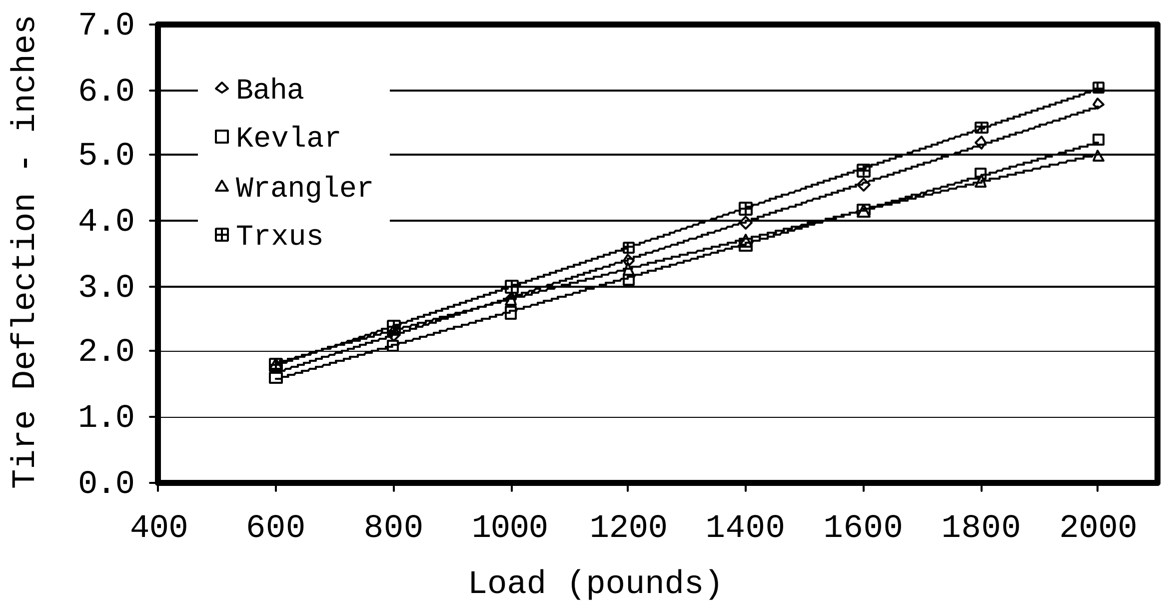

Figure C37. Plunger deflection at 15 psi.

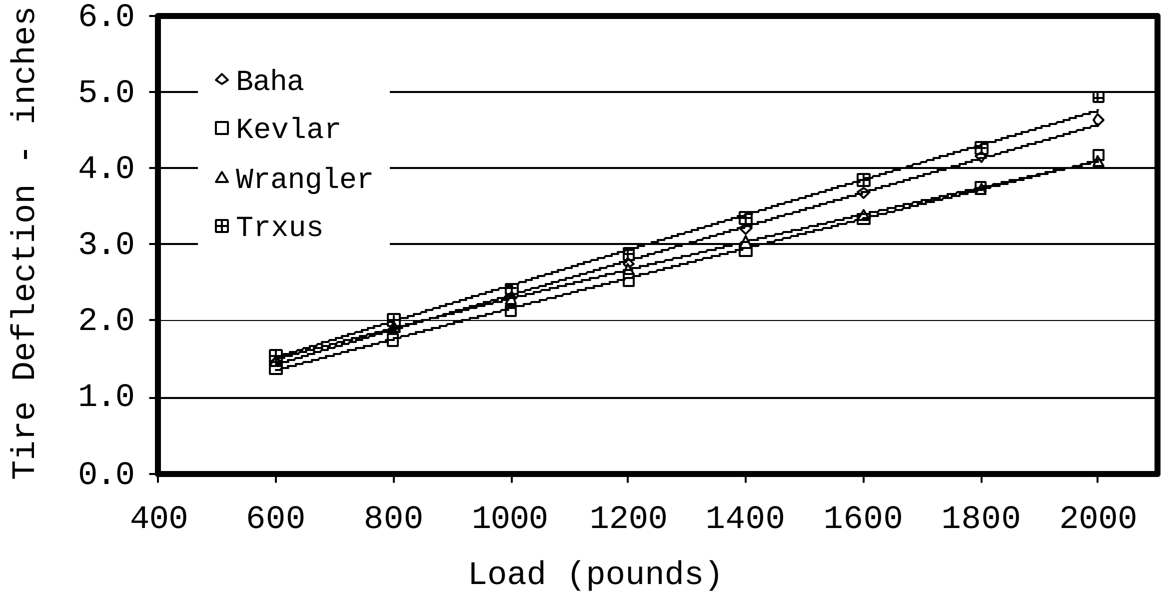

Figure C38. Plunger deflection at 20 psi.

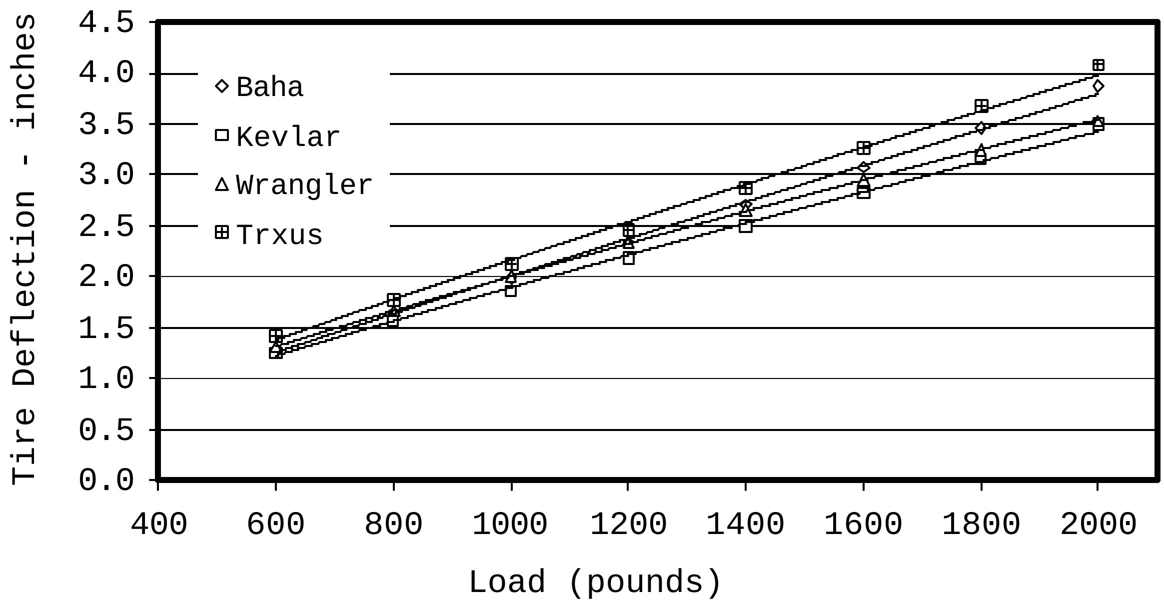

Figure C39. Plunger deflection at 25 psi.

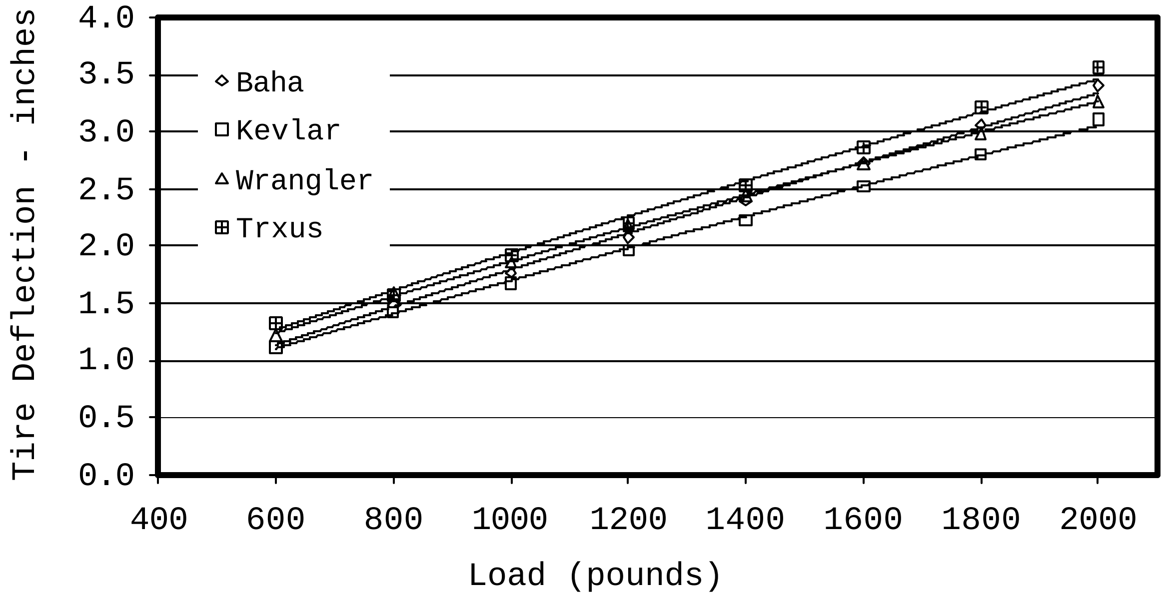

Figure C40. Plunger deflection at 30 psi.

Appendix D: Field Tests

The following field tests were conducted on the four tires used for the laboratory tests.

1. The plunger drive-over tests consisted of driving single tires over a plunger at slow speeds and measuring plunger depth.

2. Rutting tests consisted of driving a vehicle in a straight line at various pressures and measuring rut depth and disturbed width.

3. Vehicle spirals over sand at YPG were measured for rut depth and disturbed width.

4. Vehicle spirals over vegetation at YPG and Camp Atterbury were measured for disturbed width and vegetative impacts.

Tires Tested

The tires tested are shown below and are the same tires listed in Appendix C. Note the different maximum pressure and load for each tire, indicating possible different operating conditions for the tire when mounted on the vehicles.

Tire – Interco Trxus
Size - 33 x 13.50 - 16 LT
Maximum Load - 2,800 lb
Maximum Pressure - 45 psi
Load Range - D
Ply Rating - NA
Tread Ply - 6-ply polyester
Sidewall Ply - 4-ply polyester

Tire - Mickey Thompson BAHA Belted HP
Size - 33 x 12.50 - 16 LT
Maximum Load - 2,755 lb
Maximum Pressure - 45 psi
Load Range - D
Ply Rating - NA
Tread Ply - 4-ply poly + 2-ply fiberglass belts
Sidewall Ply - 4-ply poly

Tire - Kevlar Dick Cepek F-C
Size - 38 x 15.50 - 16.5 LT
Maximum Load - 3,275 lb
Maximum Pressure - 30 psi
Load Range - C
Ply Rating - A
Tread Ply - 4-ply poly + 2-ply Kevlar
Sidewall Ply - 4-ply poly cord

Tire – Goodyear Wrangler MT (Standard Military Tire)
Size - 37 x 12.5 - 16.5 LT
Maximum Load - 3,850 lb
Maximum Pressure - 50 psi
Ply Rating - 6
Tread Ply - 4-ply (2 poly and 2 steel)
Sidewall Ply - 2-ply poly cord

The ability of a tire to be driven over an obstacle (rock, etc.) and the tire conforming over the obstacle is desirable when considering terrain impact. Conformability (or ability to change shape) allows the tire to maintain contact with the ground when traveling over some obstacles while reducing the load applied to the obstacles. Although laboratory tests were conducted to evaluate conformability, plunger drive-over tests were also conducted to further evaluate tire conformity.

Procedure

The Baha, Trxus, and Wrangler tires were placed on a 1996 Dodge Ram 2500 and driven slowly over the steel plunger used in the plunger test. The Kevlar tire is a larger size and did not fit on the vehicle. The weight on each tire was approximately 1,840 lb. Each tire was tested at 30, 20, and 10 psi. Three runs were made at each pressure. Sand was placed around the plunger and a measurement was made of how close the tire got to the base of the plunger while still on the ground. Each run was video-taped, and analysis of the video revealed plunger depth into the tire and vertical axle movement.

Results

The Wrangler tire produced the lowest amount of conformability when compared to the Baha and Trxus tires. Higher axle rise (Figure D1)and lower plunger depth (Figure D2) were recorded at all pressures, indicating the Wrangler tire will ride up over obstacles, and not conform around the obstacle. This observation could be due to the two steel belts in the Wrangler tread. The other tires did not have steel belts. Lower plunger depths were recorded for the drive-over tests, probably due to the dynamics of the test.

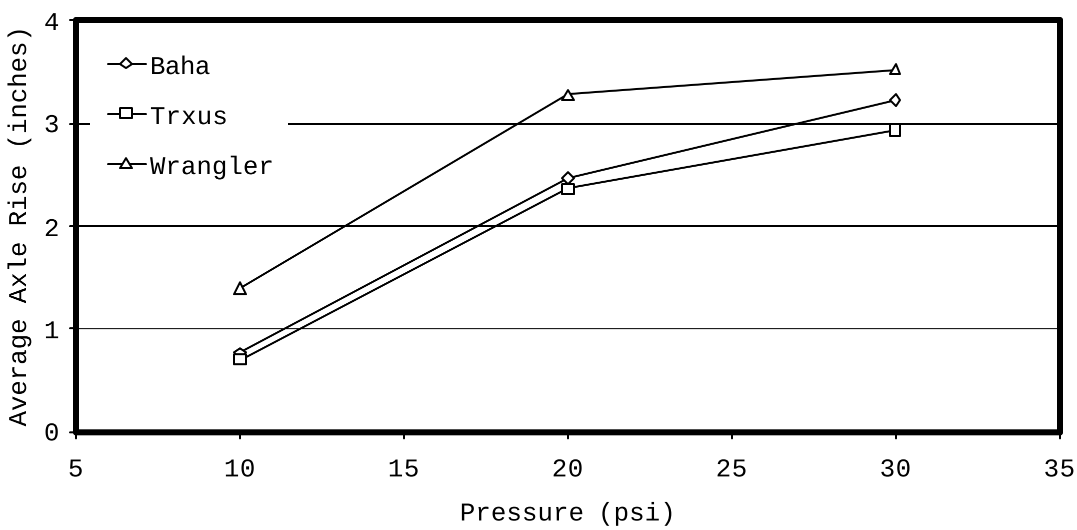

Figure D1. Axle rise for each tire.

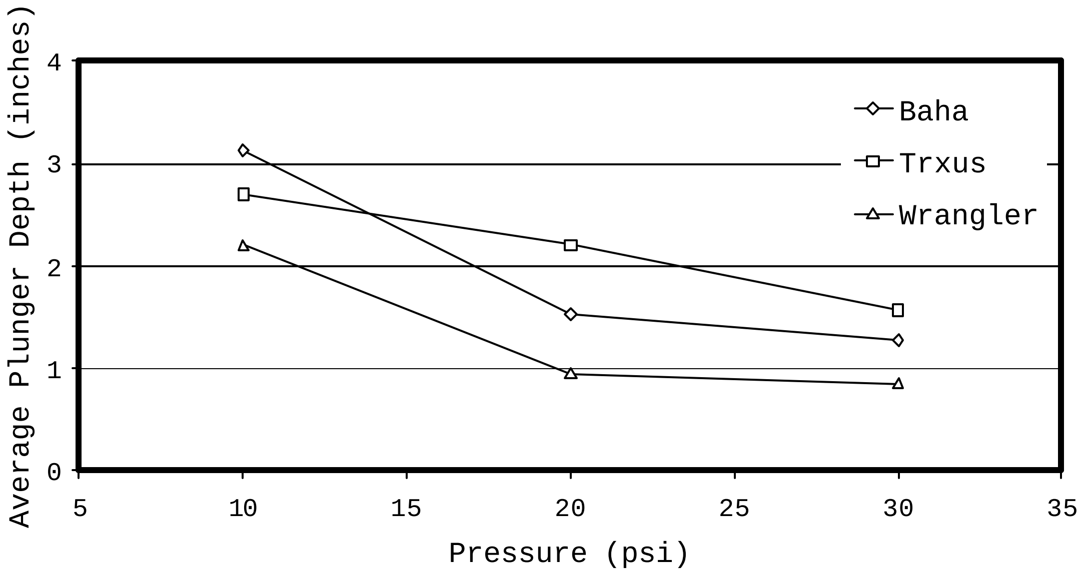

Figure D2. Plunger depth for each tire.

Rutting Field Tests

Rutting is a common terrain impact when vehicles travel off road. The degree of rutting is influenced by tire pressure, size and load, and soil conditions. Rutting is measured in terms of rut width and depth.

Procedure

The rutting field tests were conducted in March 2003 in Yuma, AZ. The Wrangler, Baha, and Trxus tires were mounted on a modified M1009 Commercial Utility Cargo Vehicle (CUCV) and slowly driven straight over a loamy sand soil. The tire configurations are shown below:

1. Wrangler - 40 psi
2. Wrangler - 20 psi
3. Baha – 24 psi
4. Baha - 15 psi
5. Trxus - 24 psi
6. Trxus - 14 psi

Two runs were made with each of the six tire configurations. Five rut width and rut depth measurements were made on both the passenger and driver sides. Cone penetrometer and drop cone measurements were also conducted to measure the soil strength.

Results

Figures D3 through D5 show the results. The Wrangler tire at 40 psi exhibited the highest rut depth and lowest rut width at both 20 and 40 psi. Generally, rut depth increased as tire pressure was increased. Rut depth and width tend to be a function of tire pressure and tire size.

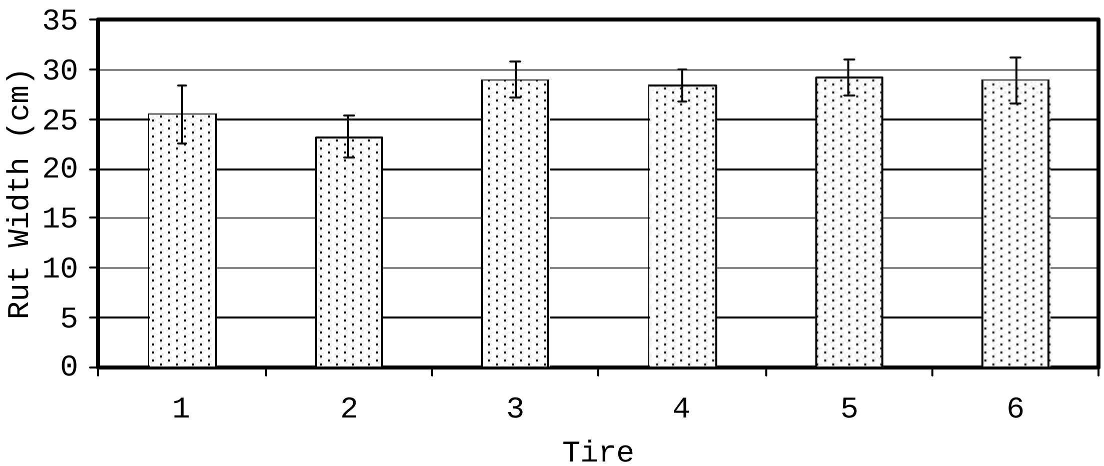

Figure D3. Average rut width.

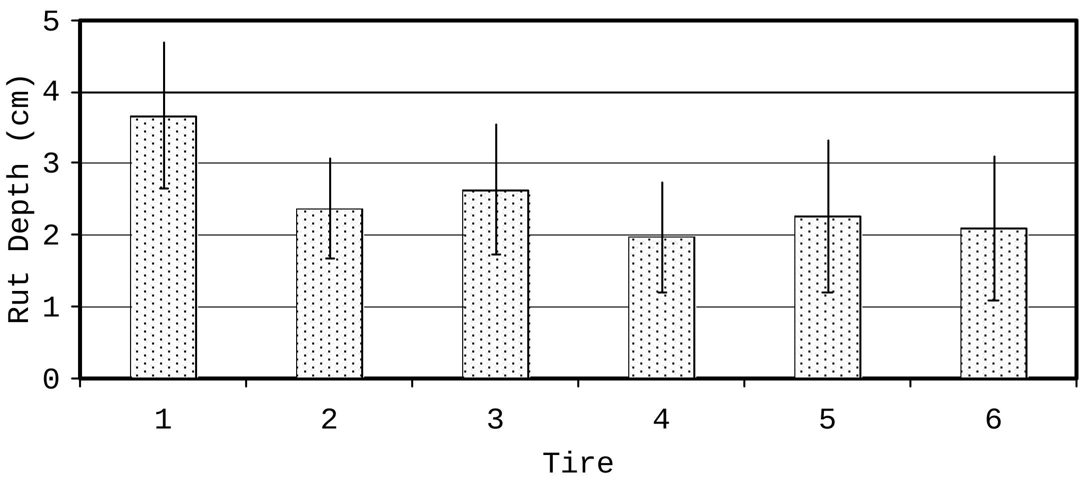

Figure D4. Average rut depth.

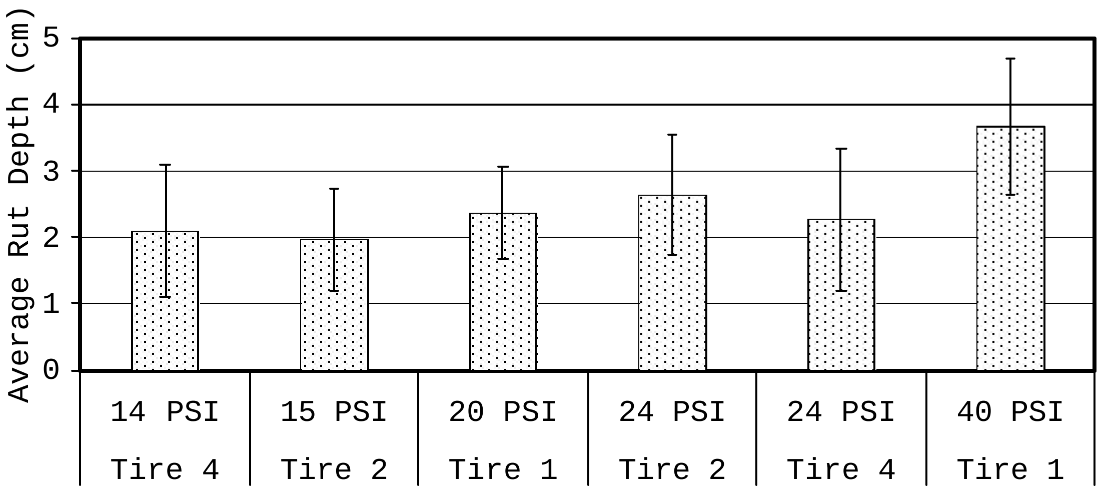

Figure D5. Average rut depth with increasing tire pressure.

The vehicle spiral tests were designed to compare the field impact of the candidate LEIF tires with regular tires under different dynamic conditions and different field surface conditions. These field tests are required to determine if differences in terrain and vegetative impacts can be observed. The LEIF tires were tested on both a sand test area and two vegetation-covered fields.

Vehicle dynamic properties, such as velocity and turning radius, play an important role in the magnitude of disturbed width (Li et al. 2003). The test vehicle can be operated in a series of spirals at both high and low speed, so that the field impact can be compared under different dynamic conditions. The spiral method was used to compare the impact characteristics of the tires under different work conditions. To conduct a fair comparison between the candidate tires and the reference tire, it is required to evaluate the impact under the same static and dynamic vehicle conditions and the same field condition. Although it is relatively easy to control the static test conditions such as field condition, vehicle weight, and tire pressure, the vehicle dynamic properties (velocity and turning radius) are at the mercy of the test driver’s skill, and are hard to control so that both spirals of the reference tire and the candidate tire are uniform. Therefore, to have valid comparison data, it is important to instruct the test driver to drive the test vehicle in spirals as uniform as possible. The vehicle dynamic properties (velocity and turning radius) are derived from the global positioning system (GPS) tracking data, which were used to track the movement of the test vehicle. The vehicle turning radius can be determined using a three-point turning radius calculation method (Haugen et al. 2000). Disturbed width and impact severity (amount of vegetation removed) of each impact type was measured at each sampling point. Rut depth and pile height were also measured. The relationships between the magnitude of field impact and vehicle turning radius were determined. Based on these relationships, the field impact of the LEIF tires was compared with that of the regular tire.

Sand Impact Field Tests

Procedure. The sand impact tests were conducted at YPG on 11 March 2003. A HUMMWV mounted with the candidate Kevlar and Goodyear tires was operated in eight spiral patterns at both high (8 m/s) and low (3 m/s) speed. Each tire setting had two high-speed operations and two low-speed operations as shown in Table D2. The Goodyear tire was the reference tire and the Kevlar, the low-impact tire.

Table D1. Tire and speed conditions for spiral tests.

Spiral	**Tire**	**Speed**
1	Kevlar	Low
2	Kevlar	High
3	Kevlar	Low
4	Kevlar	High
5	Goodyear	Low
6	Goodyear	High
7	Goodyear	Low
8	Goodyear	High

Soil impacts, including disturbed width, pile width, and rut depth, were measured along the spirals. Figure D6 shows the sand impact in the forms of both rut and pile. The GPS positions of the vehicle were collected by using the Trimble AgGPS 132 with Omnistar differential correction (Trimble, Sunnyvale, CA). The GPS data were logged every second. Dynamic properties (velocity and turning radius) were derived from the GPS data.

Figure D6. Sand impact.

Soil samples of each spiral were collected and analyzed by the Soil, Water and Plant Testing Laboratory at Colorado State University, Fort Collins. Table D2 shows that the texture of the field is sand, which composes more than 95 percent of the soil.

Table D2. Soil analysis of the sand field.

Spiral No.	**Moisture**	**Sand**	**Silt**	**Clay**	**Texture**
1	0.35	96	2	2	Sand
2	0.25	96	2	2	Sand
3	0.22	98	0	2	Sand
4	0.52	97	1	2	Sand
5	0.24	95	3	2	Sand
6	0.34	96	2	2	Sand
7	0.37	96	2	2	Sand
8	0.27	94	4	2	Sand
Average	0.32	96	2	2	

The dynamic property of the soil was determined by drop cone measurement. Figure D7 shows the drop cone measurement data at each sampling point along spirals 4 and 8. The soil strength property is very uniform along the spirals, with the average drop cone measurement of 10.8 cm.

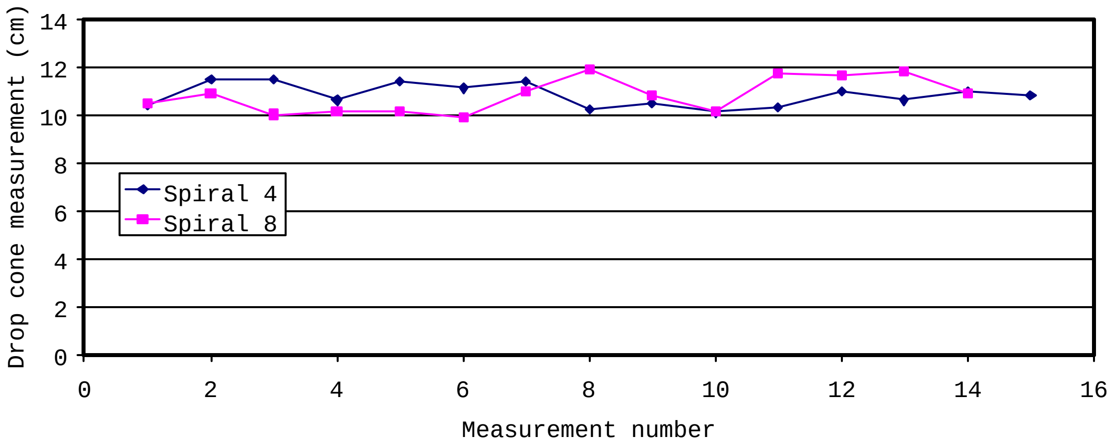

Figure D7. Sand field drop cone measurement.

Test vehicle. Figure D8 shows the HMMWV test vehicle (model number 1097A1). The candidate low-impact tire is the 38/15.50X16.5 LRC Dick Cepek F-C Kevlar. The reference tire is the 37/12.50R16.5LT LRD Goodyear MT.

Figure D8. Sand impact test vehicle.

The vehicle weight specifications are:
Curb weight: 5,600 lb
Max GVW: 10,000 lb
Actual weight: 5,750 lb (3,100 lb front axle, 2,650 lb rear)

The soil impact data were determined at each point shown in Figure D9. The figure shows the GPS tracking positions of the sand impact spirals.

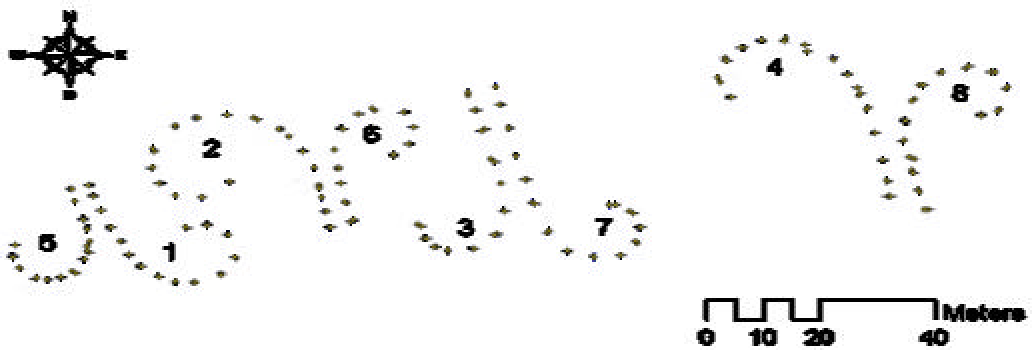

Figure D9. Sand spiral impact points.

Results. Figures D10 and D11 show the imprint width plus pile width plotted against the turning radius for Kevlar low-impact tires and Goodyear tires, respectively. Both figures are of low speed setting and driver-side track. These figures show that the smaller the turning radius, the larger the soil disturbed width. The disturbed width dramatically decreases at smaller turning radii. The curve levels off at larger turning radii. Since the influence of turning radius to soil disturbance diminishes as it increases, any turning radius with values of more than 150 meters is treated as 150 meters in the analysis.

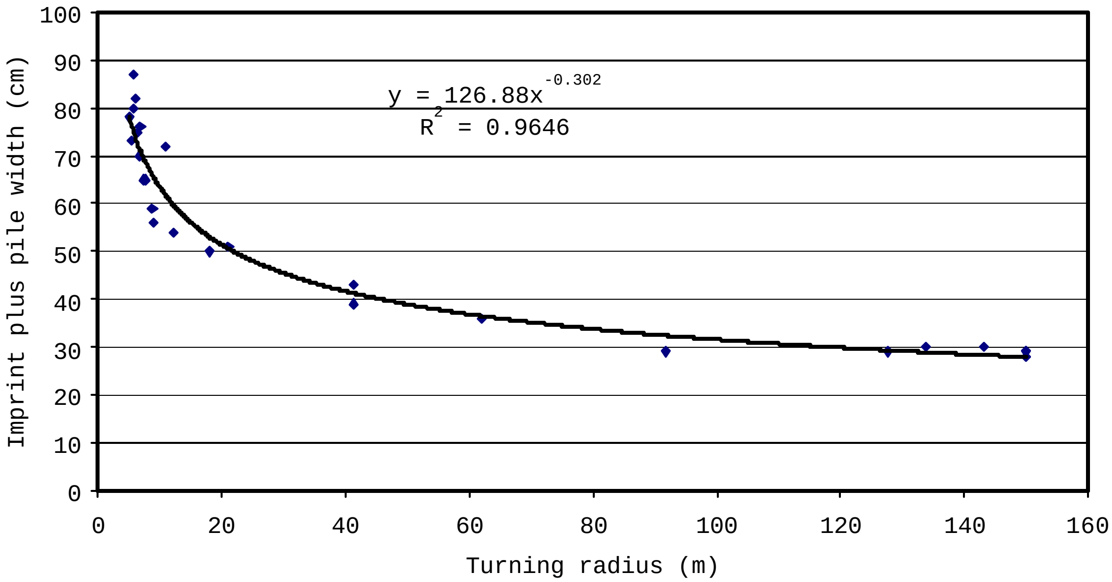

Figure D10. Kevlar low-speed driver-side track impact.

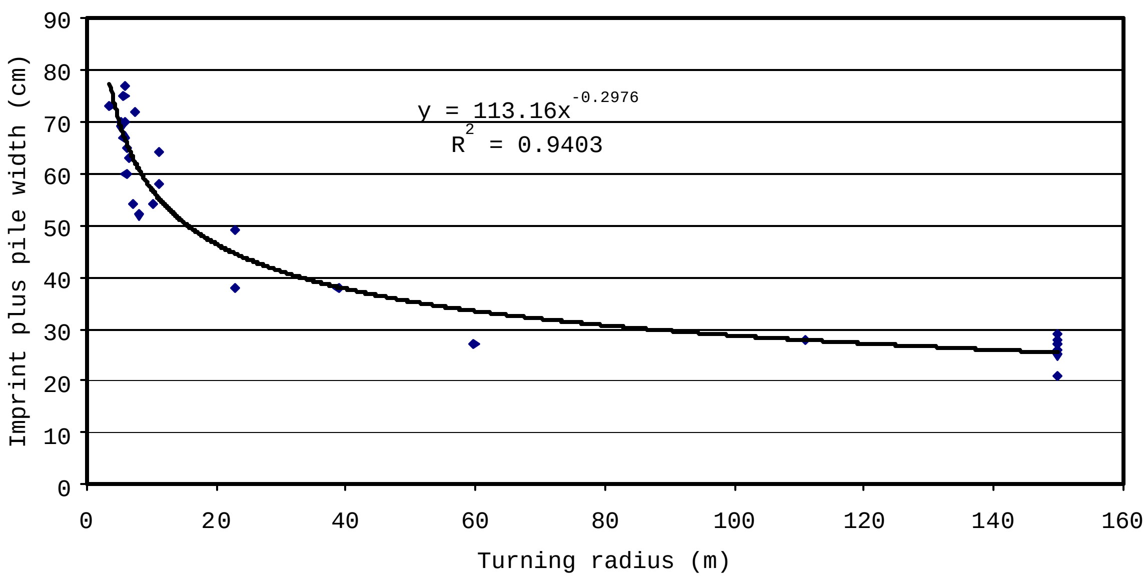

Figure D11. Goodyear tire low-speed driver-side impact.

Figures D12 and D13 show the comparison of the impact relations of Kevlar tires and Goodyear tires on the driver-side track and passenger-side track, respectively. Both high speed and low speed were compared. It was found that the Kevlar tires and the Goodyear tires have very similar impact characteristics on sand. The Kevlar tire exhibited a slightly higher disturbed width, probably due to the wider tire.

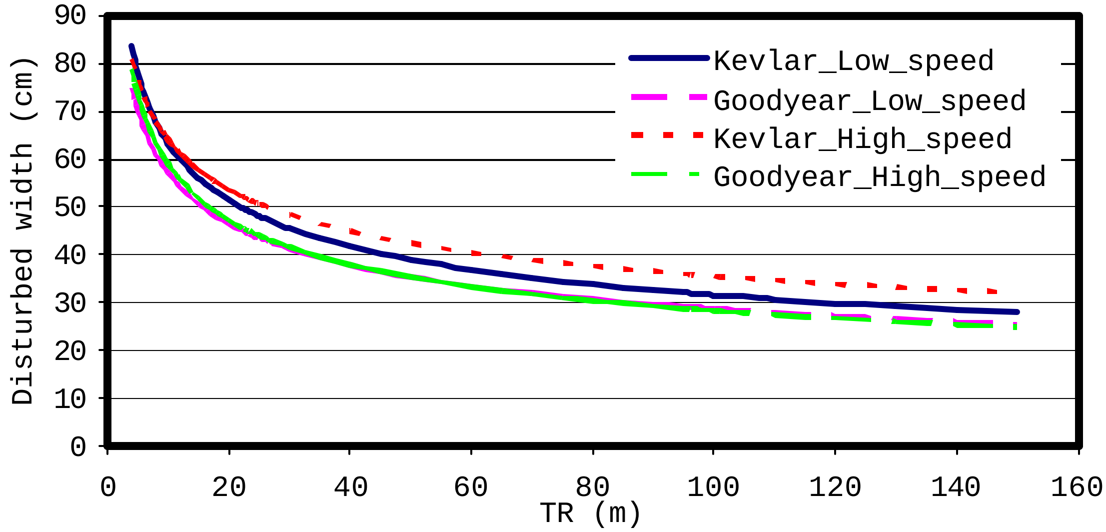

Figure D12. Driver-side impact comparison.

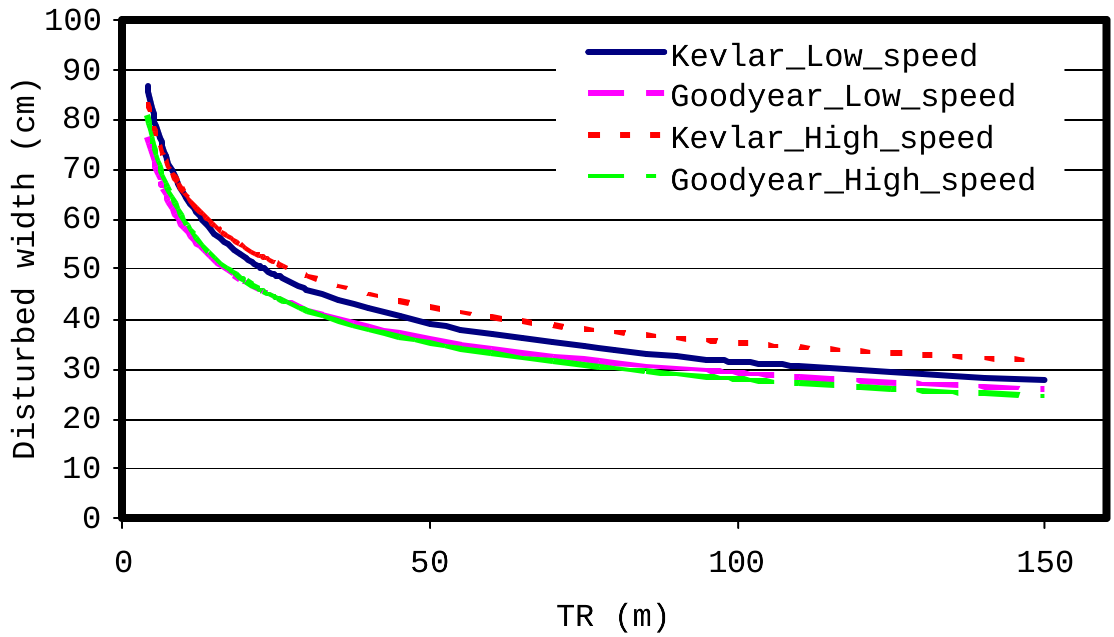

Figure D13. Passenger-side impact comparison.

A smaller turning radius usually causes an increased rut depth. Figures D14 and D15 show the relationship between rut depth and turning radius for Kevlar and Goodyear tires, respectively, at low speed. Rut depth measurements at slow speed were variable with low R square values for equation fits.

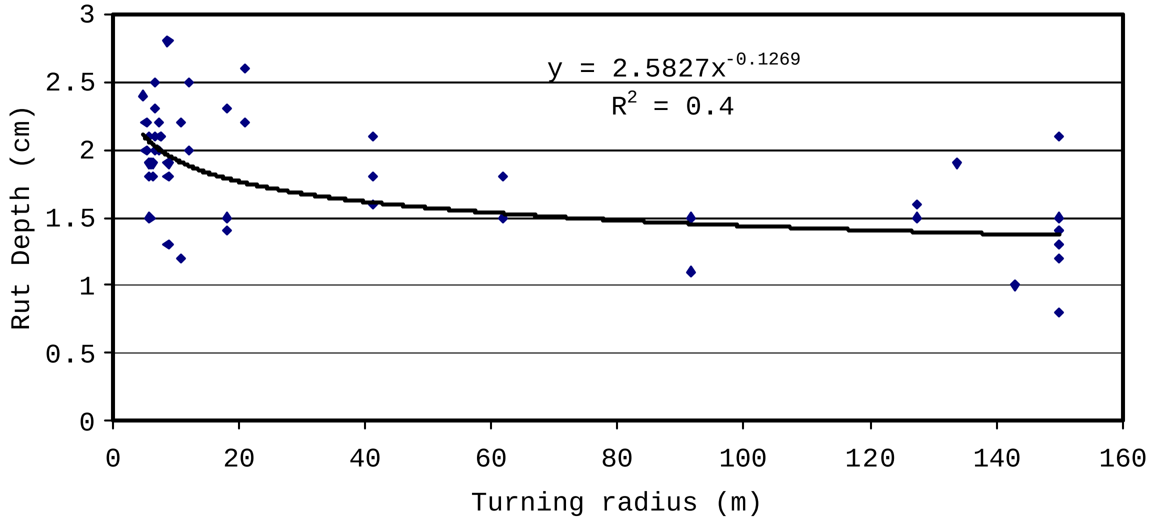

Figure D14. Rut depth of Kevlar tire at low speed.

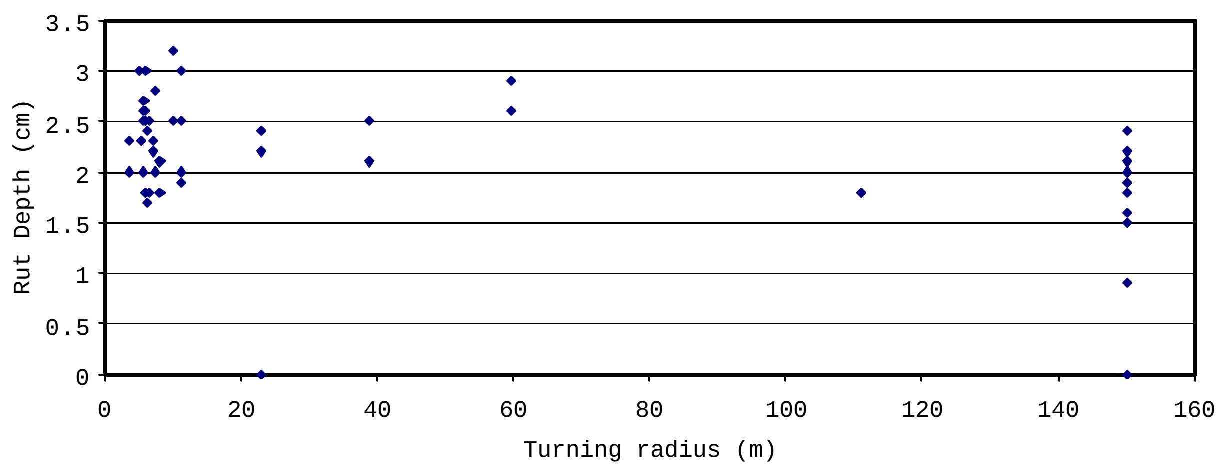

Figure D15. Rut depth of Goodyear tire at low speed.

At high speeds, the Kevlar tire (Figure D16) exhibited lower rut depths when traveling straight, and higher rut depths when turning as compared to the Goodyear tire (Figure D17).

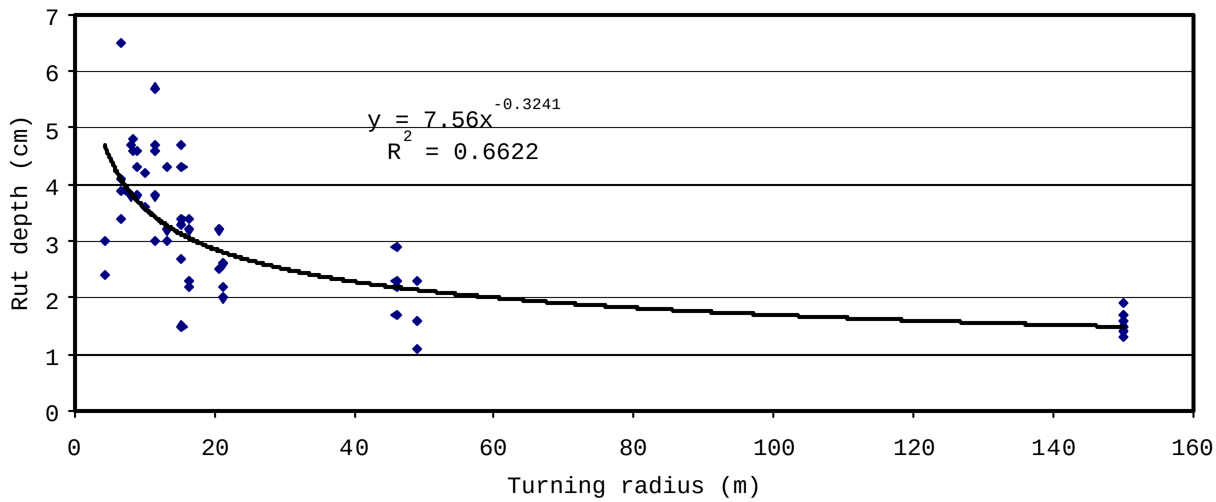

Figure D16. Rut depth of Kevlar tire at high speed.

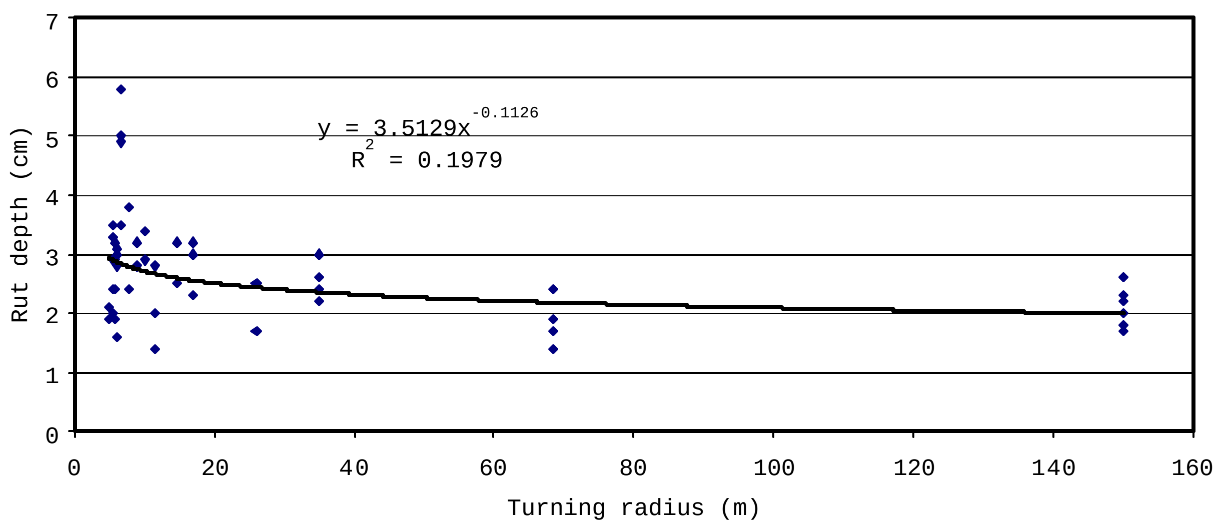

Figure D17. Rut depth of Goodyear at high speed.

Vegetative Impact Field Tests

Yuma Proving Ground procedures. The grass impact test was conducted on a grassland site at YPG on 12 March 2003. The test vehicle was an M1008 CUCV, which is a 4X4 5/4-ton cargo truck with a ground vehicle weight of 8,800 lb. Cooper Discoverer H/T LT 235/85R16 and Mickey Thompson BAHA Belted HP 33x12.5-16LT tires were tested. For the Cooper tire, the maximum load/ pressure rating was 3,042 lb at 80 psi. The measured tire pressure ranged from 40 to 43 psi. The Cooper tire is similar to the standard radial Goodyear tire. For the Mickey Thompson tire, the maximum load/pressure rating was 2,755 lb at 45 psi. The measured tire pressure ranged from 25.4 to 25.6 psi.

Figure D18. Vegetative impact test vehicle.

As with the sand impact field tests, the GPS positions of the vehicle were collected by using the Trimble AgGPS 132 with Omnistar differential correction. The GPS data were logged every second. Dynamic properties (velocity and turning radius) were derived from the GPS data.

Figure D19 shows the GPS tracking points of the vehicle collected along the eight spirals. The field impact width was plotted against the vehicle turning radius in order to indicate their relationships.

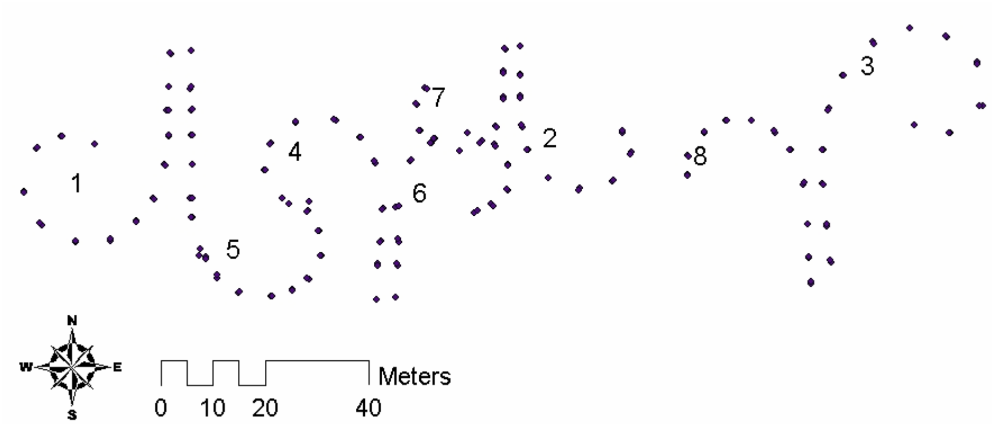

Figure D19. Vegetative spiral impact points.

Eight spirals were conducted. Each tire (Mickey Thompson and Cooper) setting had two high-speed operations (5.7 m/s) and two low-speed operations (3.9 m/s). Impact measurements of disturbed width were taken for each impact type at each sampling point.

Yuma Proving Ground results. Impact severity is the percentage of vegetation that has been removed or scraped from the disturbed area. Figure D20 illustrates measurement of the vegetative impact. Because the soil strength of the field was strong and the test vehicle was not heavy, high values of impact severity were not visually observed in the test, so impact comparisons were conducted using disturbed width.

Figure D20. Vegetative impacts are measured.

The soil type, soil strength, and vegetation coverage of the test field were uniform. The soil components of the vegetative test field, however, were very different from the sand field. Table D3 shows the analysis results for soil samples of each spiral (Soil, Water and Plant Testing Laboratory, Colorado State University). The soil texture is clay. Unlike the analyses of the sand field, there is no dominant component in the soil sample of the vegetative field. The two major components of the vegetative land are clay and sand; 47.9 and 34.75 percent of the total weight, respectively.

The dynamic property of the soil was determined by drop cone measurement. Figure D21 shows the drop cone measurement data at each sampling point along spirals 3 and 6. The average drop cone measurement is 7.4 cm. The soil strength is much higher than the sand field, which had an average drop cone measurement of 10.8 cm.

Table D3. Soil analysis of the grass test area.

Spiral No.	Moisture	Sand	Silt	Clay	Texture
1	8.3	34	18	48	Clay
2	9.21	38	16	46	Clay
3	8.97	34	19	47	Clay
4	9.23	33	17	50	Clay
5	8.85	34	16	50	Clay
6	9.74	36	18	46	Clay
7	8.8	34	17	49	Clay
8	8.14	35	18	47	Clay
Average	8.91	34.75	17	47.9	

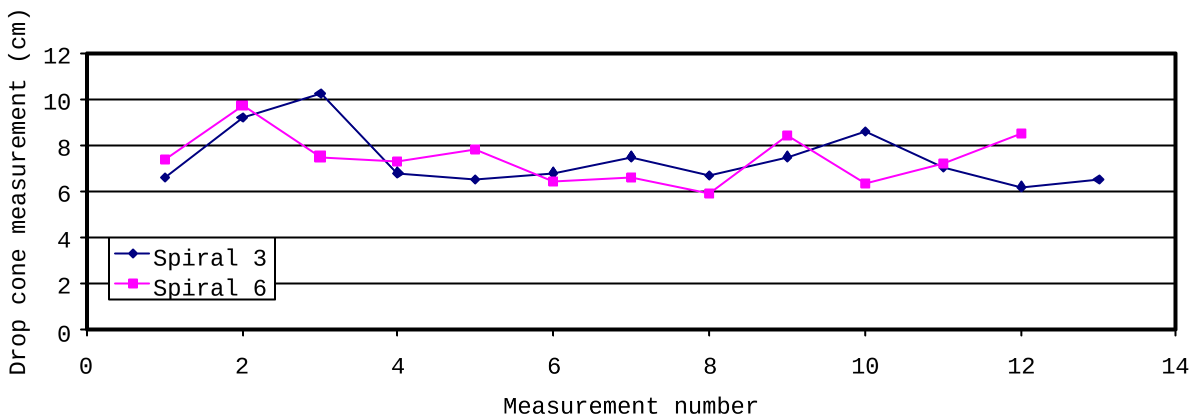

Figure D21. Vegetative field drop cone measurement.

Figures D22 and D23 show the disturbed width plotted against the turning radius for Cooper and Mickey Thompson tires, respectively. Both of the graphs illustrate the tires operated at a high-speed setting and on the driver-side track. Similar impact patterns as sand field test were observed. Both figures show that the smaller the turning radius the larger the soil disturbed width. The disturbed width dramatically decreases at smaller turning radii. The influence of turning radius to field impact diminishes as it increases. Any turning radius with a value of more than 150 m is treated as 150 m in the analysis.

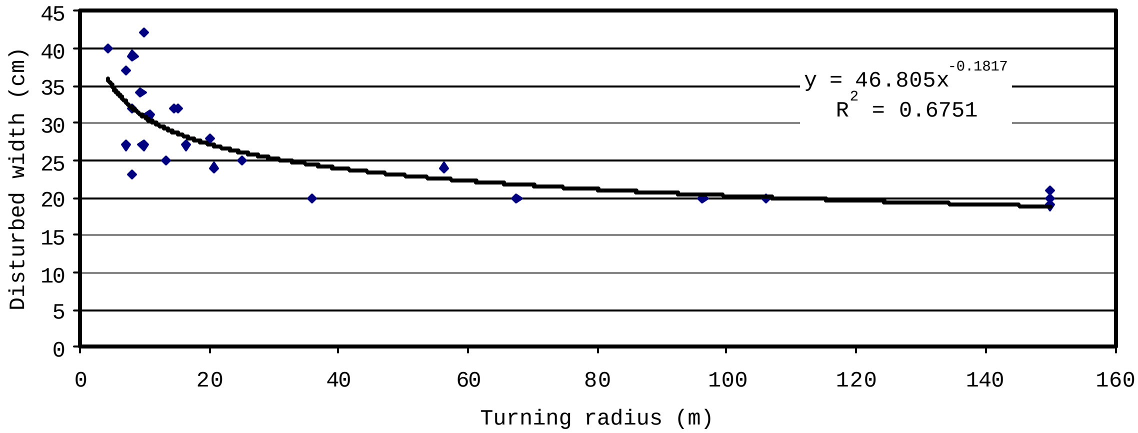

Figure D22. Cooper tire high-speed driver-side impact.

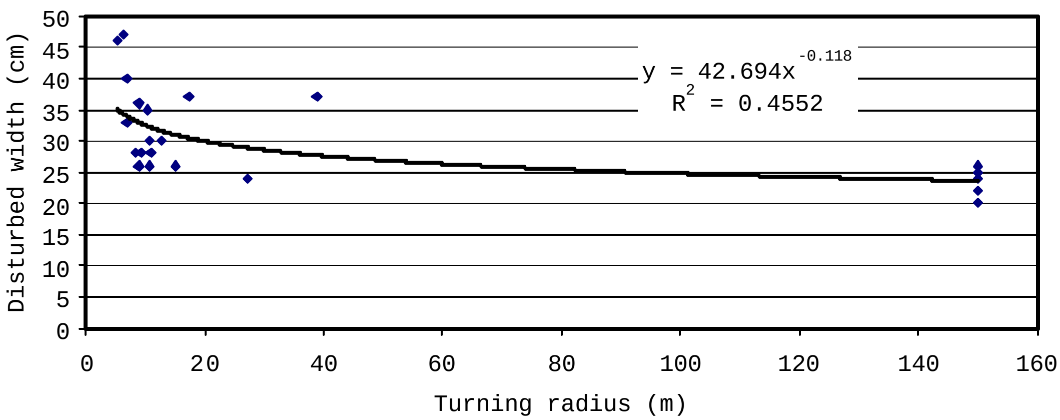

Figure D23. Mickey Thompson tire high-speed driver-side impact.

Camp Atterbury procedures. The grass impact test was conducted on a site at Camp Atterbury on 28 May 2003. The two test vehicles were:

1. M1025 1-1/4-ton Utility Truck with Kevlar 38x15.5-16.5 tires (tire pressure range 25.6 to 28.2 psi)

2. M998 1-1/4-ton Utility Truck 4x4 with Wrangler R/T II Military OZ 36x12.5-16.5 tires (tire pressure range 13.8 to 19.2 psi).

Four spirals were conducted with each vehicle (two high-speed and two low-speed). Impact measurements of disturbed width and impact severity were taken at each sampling point along the spiral. Impact severity is the percentage of vegetation that has been removed or scraped from the disturbed area and is determined using a guideline for assigning impact severity values (Haugen et al. 2000). Cumulative impact width can be calculated by multiplying disturbed width and impact severity. The GPS positions of the vehicle were collected by using the Trimble AgGPS 132 with Omnistar differential correction. The GPS data were logged every second. Dynamic properties (velocity and turning radius) were derived from the GPS data.

The M1025 (Kevlar tire) and M998 (Wrangler tire) were operated in four spirals each (two high-speed and two low-speed). High- and low-speed operations were conducted at approximately 3 and 6 m/s, respectively. The vegetative impacts were low for both tires, and vehicle speed did not influence impact.

Camp Atterbury results. Figure D24 shows the cumulative impact width plotted against the turning radius for the Wrangler and Kevlar tires for the combined speeds and both driver and passenger-side track. As shown before, the smaller the turning radius the larger the terrain impact. The Kevlar tire produced slightly larger impacts than the Wrangler tire. However, variables such as different vehicle, different driver, and variable soil and vegetative conditions may have influenced these results. The Kevlar tire had a larger width than the Wrangler tire.

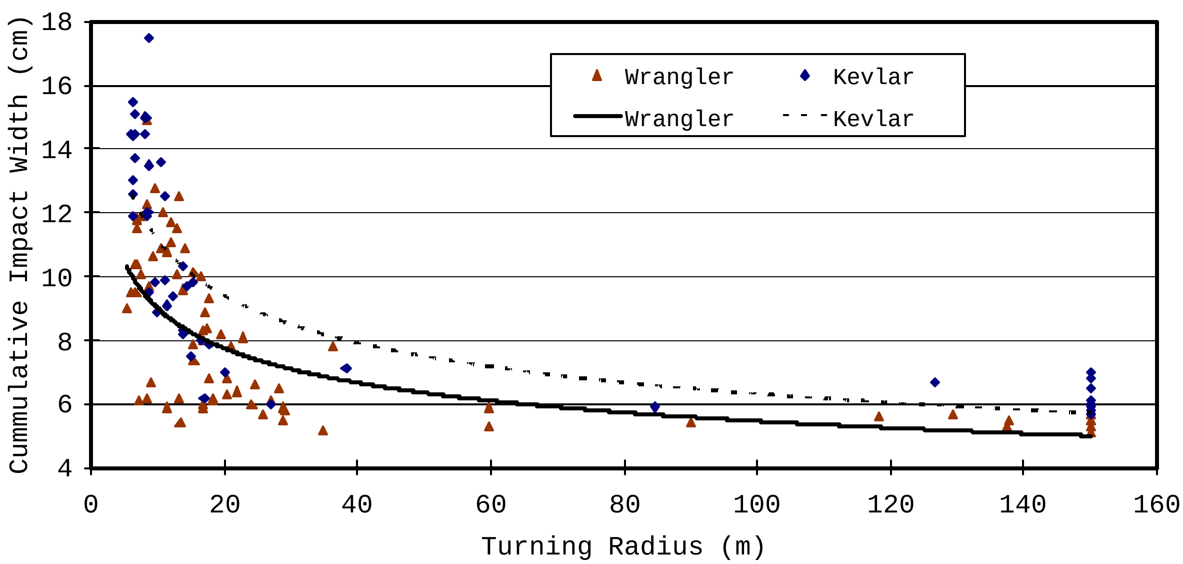

Figure D24. Tire impact comparison.