EasyChair Preprint

№ 1400

Update from a Multi-Year Data Mining Effort on Drove: Database Records for off-Road Vehicle Environments

Farshid Vahedifard, Isaac Howard, Arman Borazjani, George Mason and Jody Priddy

August 13, 2019

UPDATE FROM A MULTI-YEAR DATA MINING EFFORT ON DROVE: DATABASE RECORDS FOR OFF-ROAD VEHICLE ENVIRONMENTS

Farshid Vahedifard[a,b], **Isaac L. Howard**[a,b], **Arman Borazjani**[a,b], **George L. Mason**[a,b], **Jody D. Priddy**[c]

[a] *Dept. of Civil and Environmental Engineering, Mississippi State University, Mississippi State, MS 39762, USA*
[b] *Center for Advanced Vehicular Systems (CAVS), Mississippi State University, Mississippi State, MS 39762, USA*
[c] *U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Rd, Vicksburg, MS 39180, USA*
farshid@cee.msstate.edu, ilhoward@cee.msstate.edu, ab3132@msstate.edu, mason@cavs.msstate.edu, Jody.D.Priddy@usace.army.mil

---

Abstract

This paper presents an update from a multi-year research program to create and expand the Database Records for Off-road Vehicle Environments (DROVE), one of the most comprehensive physical testing databases for off-road vehicles in existence. DROVE was created and has been expanded by a multi-year data mining effort through published and unpublished data assembled from several technical reports for laboratory and field tests spanning decades of testing with wheeled and tracked vehicles on different soil types. The first edition of the database (DROVE 1.0) included over eight thousand records from the existing archives of laboratory and field tests of wheels operating on loose sand and high plasticity clay. DROVE 1.0 included results from tests performed by wheels of different diameters, widths, heights, and inflation pressures, operating under varying loading conditions. DROVE 2.0 added 294 test results from powered and unpowered tracks on fine-grained soils, and release of DROVE 3.0 is pending and as envisioned would provide hundreds of digital files of mobility data to the terramechanics community. The DROVE structure is assembled to include various traction performance parameters such as drawbar pull, torque, traction, motion resistance, sinkage, and wheel slip. DROVE provides the mobility community with a resource to evaluate existing soil mobility algorithms and also, to develop improved algorithms to assess performance of various wheel designs. The authors compared DROVE to the algorithms currently defined in the Vehicle Terrain Interface (VTI) for mobility modeling of wheeled vehicles. Comparison of the predicted versus measured performance parameters are presented for different soil types. This study provides insight into what published data exists, what are the bounds on the data, and how the data matches algorithms predicting forces between wheel and/or track and the soil such as VTI.

Keywords: Off-Road Mobility, Database Records for Off-road Vehicle Environments (DROVE); Data Mining, Wheels, Tracks, Drawbar Pull, Motion Resistance, Sinkage

---

1. Introduction

Off-road vehicle performance over various terrains is an important area of study with extensive applications in the military, agriculture, and construction sectors. Early investigations in this field were primarily conducted through trial and error approaches among various industries. Increased interest over improved land vehicular mobility by the military in the 1950s spurred further study. Over the past several decades numerous field and laboratory studies have been conducted assessing the performance of wheeled and track vehicles over different sand and clay types (e.g., Wismer, 1966; Turnage, 1972; Kraft et al., 1971a, 1971b; Frietag, 1965). The studies, comprised of high-volume empirical testing, were conducted using full vehicle systems in the field and a single element dynamometer system set up over a series of soil bins in the lab. Records documenting details and results from individual tests were included. Subsequently, the results obtained from these experiments were used to better the understanding between vehicle and soil interaction.

In addition to the relevant conclusions and determinations that arose from early terramechanics experimentation, the data obtained in records documenting the experimentations are still of value. Results from these records provide high quantities of measured results that can be utilized to develop and improve new and existing models, through predicted versus measured relationships. The experimental results are also valuable due to the cost of maintaining and operating such field and laboratory systems. Despite the value in these records and the large quantity of data available there remains a lack of direct, consolidated access to such records. As such, Mississippi State University through the Center for Advanced Vehicular Systems (CAVS) and the U.S. Army Engineer Research and Development Center (ERDC) began to produce a consolidated database comprised of such records available through ERDC. The developed database was named Database Records Off-road Vehicle Environments (DROVE) and since its conception in 2013 has continued to acquire new records as they become available. This paper serves as an update on the development of DROVE and its related applications.

2. DROVE AND OVERALL PROJECT

DROVE is an ongoing effort and it is expected to incorporate new records as they become available. Primary features of the currently contained records or potential records may include: test type, tire/track dimensions, loading, soil strength, turn angle, tire deflection, sinkage, drawbar pull, motion resistance, and torque. To date, work on the database has resulted in the release of versions DROVE 1.0 (Vahedifard et al., 2016, 2017) and DROVE 2.0 (Williams et al., 2019a). This initial database version contains data from technical reports from the Defense Information and Technology Center; other libraries were also searched. Further description of DROVE 1.0 can be found in the following subsection. Since the completion of DROVE 1.0, data from an unpublished repository centered around tracked vehicle operation on clay soils has been obtained. The addition of this dataset to the DROVE database has been cause for the creation of DROVE 2.0 and subsequently DROVE 3.0 (Howard et al., 2019) is drafted and under sponsor review. Other information has also been identified that is a candidate for DROVE releases beyond 3.0.

2.1 DROVE 1.0

DROVE 1.0 (Vahedifard et al., 2016, 2017) consisted of records for wheeled vehicles operating in sands and clays. The data reports were downloaded in adobe format and converted to digital spreadsheets using character recognition software. Thereafter, data were plotted and compared to the existing reports, thus allowing detection of conversion issues. DROVE 1.0 consisted of wheeled vehicle and dynamometer testing with 5,522 coarse-grained soil test records and 2,657 fine-grained soil test records for a total 8,179 records. While a small number of steered and high speed tests were conducted in the laboratory data sets, a majority of records focused on speeds less than 5 m/s for a non-steered wheel operating in a braked, towed, or powered mode. Tests contained in the sand section of DROVE were conducted on dry sands including: beach, mortar, and Yuma sand. Clay testing was conducted primarily in Vicksburg Buckshot clay, though some lean clays were also tested in smaller datasets. Initial studies with the DROVE 1.0 database include comparison to existing off-road vehicle models to define uncertainty based on field tests. The database has also been successfully used to show how modifications to equations reduce uncertainty. DROVE 1.0 has future uses in stochastic modelling, supporting uncertainty analysis of off-road predictions based on variance observed in the laboratory. Fig. 1 shows the histogram distribution of performance parameter representing the tire characteristics operating in sands in DROVE 1.0 and Fig. 2 shows the histogram distribution of the traction performance parameters of wheeled vehicles operating in sands in DROVE 1.0 (Vahedifard et al., 2016).

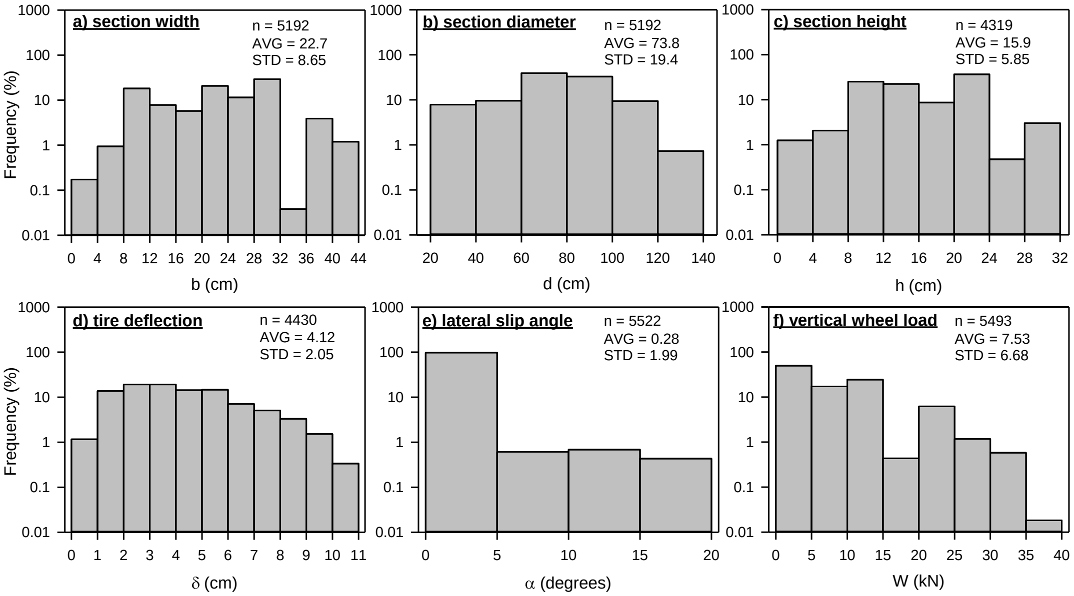


Fig. 1. Histogram distribution of performance parameters representing the tire characteristics operating in sands in DROVE 1.0 (Vahedifard et al., 2016).

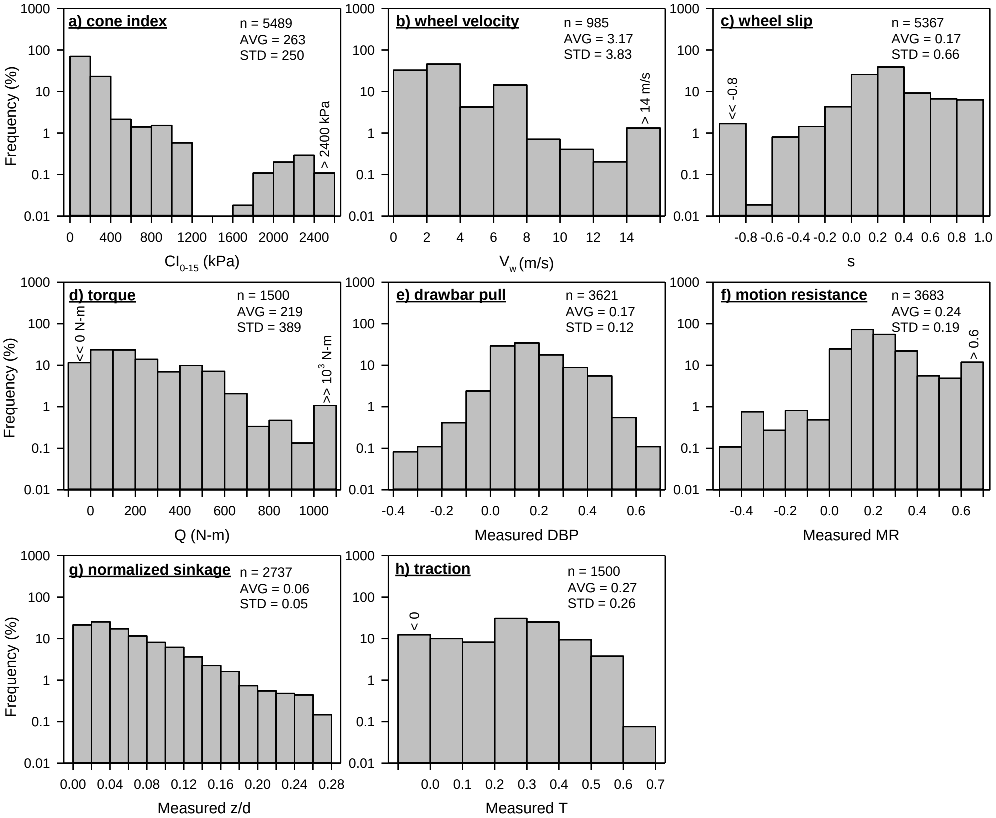


Fig. 2. Histogram distribution of the traction performance parameters of wheeled vehicles operating in sands in DROVE 1.0 (Vahedifard et al., 2016).

Figs. 3 and 4 show similar histogram distributions, along with statistical values n and AVG, representing the tire characteristics and performance parameters of wheeled vehicles operating in clays on DROVE 1.0 (Vahedifard et al., 2017). In Fig. 3 All 1222 tests contained, or provided sufficient information to estimate, values for b and d. However, a limited number of tests (72) did not record section height, leaving 1150 records. Similar to Fig. 1 and 2, δ and z are normalized by d. In addition, in Fig. 3, DBP (Fig. 3e) and MR (Fig. 3f) are coefficients normalized by W.

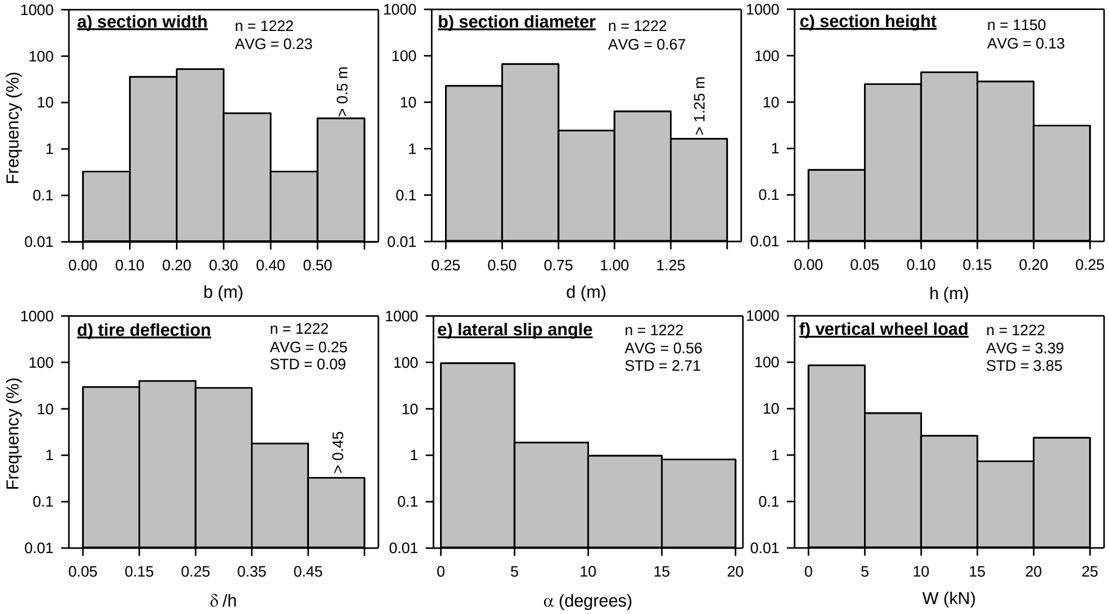


Fig. 3. Histogram distribution of performance parameters representing the tire characteristics operating in clay in DROVE 1.0 (Vahedifard et al., 2017).

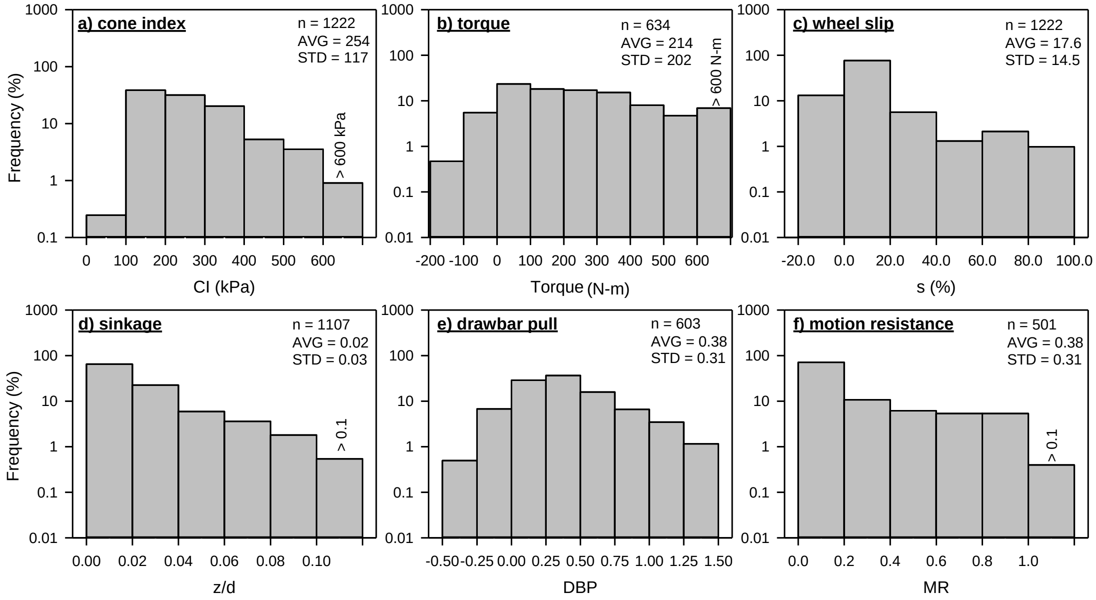
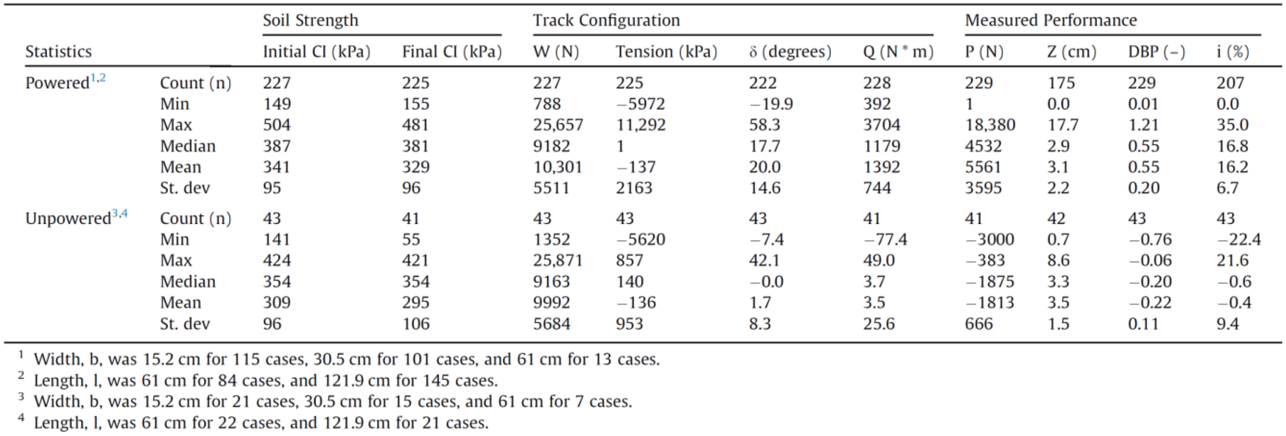


Fig. 4. Histogram distribution of the traction performance parameters of wheeled vehicles operating in clay in DROVE 1.0 (Vahedifard et al., 2017).

2.2 DROVE 2.0

DROVE 2.0 (Williams et al. 2019a) included the addition of records focusing on the performance of tracked vehicles on fine-grained soils to DROVE 1.0. The records were provided as a collection of physical files from ERDC from the 1970s, in which a full-scale track simulation system was built and operated. The records were scanned to produce adobe documents that could be converted to digital spreadsheets in a similar fashion to the reports used in DROVE 1.0. There were 294 additions to DROVE from release 1.0 to release 2.0 (Williams et al., 2019a). The number of newly added records provided by this data is small compared to the number of wheeled records contained in DROVE 1.0, but their tracked nature make them a meaningful contribution to the database. Readers should not directly associate the number of records to the value of any given record in any DROVE release. Of these records, 229 could be filtered to match powered criteria while only 43 records matched unpowered criterial. It is noted that there is a loss of 22 records for this filtering method and the records have been reviewed thoroughly to minimize errors. Despite this effort, there are some noticeable discrepancies in some outlying values, such as negative sinkage values, that require careful review and filtering before applying the dataset to a given problem. However, these values occur rarely and do not indicate a problem with the digitization scheme or the overall dataset. When working with data that is decades old in some cases, some approximation and loss of fidelity of data over time should be expected. DROVE 2.0 has future applications including the evaluation of existing mobility models, development of improved algorithms, and validation of numerical simulations for tracked vehicles. Table 1 shows summary statistics of filtered data included in DROVE 2.0 for tracked vehicles on fine-grained soils for both powered and unpowered test types (Williams et al., 2019a). The statistics include the number of records (n), minimum value (min), maximum value (max), median, and standard deviation (St. dev).

Table 1. Summary statistics of filtered data included in DROVE 2.0 for tracked vehicles on fine-grained soils (Williams et al., 2019a).



		Soil Strength		Track Configuration				Measured Performance			
Statistics		Initial CI (kPa)	Final CI (kPa)	W (N)	Tension (kPa)	δ (degrees)	Q (N * m)	P (N)	Z (cm)	DBP (–)	i (%)
Powered[1,2]	Count (n)	227	225	227	225	222	228	229	175	229	207
	Min	149	155	788	–5972	–19.9	392	1	0.0	0.01	0.0
	Max	504	481	25,657	11,292	58.3	3704	18,380	17.7	1.21	35.0
	Median	387	381	9182	1	17.7	1179	4532	2.9	0.55	16.8
	Mean	341	329	10,301	–137	20.0	1392	5561	3.1	0.55	16.2
	St. dev	95	96	5511	2163	14.6	744	3595	2.2	0.20	6.7
Unpowered[3,4]	Count (n)	43	41	43	43	43	41	41	42	43	43
	Min	141	55	1352	–5620	–7.4	–77.4	–3000	0.7	–0.76	–22.4
	Max	424	421	25,871	857	42.1	49.0	–383	8.6	–0.06	21.6
	Median	354	354	9163	140	–0.0	3.7	–1875	3.3	–0.20	–0.6
	Mean	309	295	9992	–136	1.7	3.5	–1813	3.5	–0.22	–0.4
	St. dev	96	106	5684	953	8.3	25.6	666	1.5	0.11	9.4

[1] Width, b, was 15.2 cm for 115 cases, 30.5 cm for 101 cases, and 61 cm for 13 cases.
[2] Length, l, was 61 cm for 84 cases, and 121.9 cm for 145 cases.
[3] Width, b, was 15.2 cm for 21 cases, 30.5 cm for 15 cases, and 61 cm for 7 cases.
[4] Length, l, was 61 cm for 22 cases, and 121.9 cm for 21 cases.

Fig. 5 and 6 display trends associated with the CP to CI ratio and various traction performance parameters contained in the DROVE 2.0 dataset (Williams et al., 2019a). Fig 5. illustrates the relationship present between the CP to CI ratio against DBP. Based on the regression analysis, the 2nd order polynomial equation provided for DBP allowed for the maximum coefficient of determination value (R^2) of 0.51. The strong linear trend present between CP/CI and DBP present in Fig. 5 was anticipated based on validation studies conducted around the time in which testing was performed (Turnage, 1995). This is a good indicator of the validity of the data present in DROVE 2.0. Fig. 6 illustrates the relationship between CP/CI and z. Initially, the relationship with sinkage was not as robust as the DBP relationship with CP/CI as indicated by the higher scatter in Fig. 6a. The highest R^2 obtained was 0.15 using a 2nd order polynomial which failed to indicate an apparent correlation between sinkage and CP/CI. This relationship was further investigated as a horizontal band of data points for sinkage values less than 1.3 cm was noticed. Subsequently, all sinkage values less than one half of the track shoe were filtered leading to an improved R^2 of 0.21. In total, 36 records were removed. Another linear fit using regression through the origin was run around the fact that as CP/CI approaches zero, sinkage should additionally approach zero (Fig. 6b). This new regression provided a higher R^2 of 0.21 using a slope (m) of 22.5. Bounds were incorporated around m=55 and m=10 to illustrate scatter around the fit equation. Additional bounds were input in Fig. 6c around m=35, and m=15 to further this visualization.

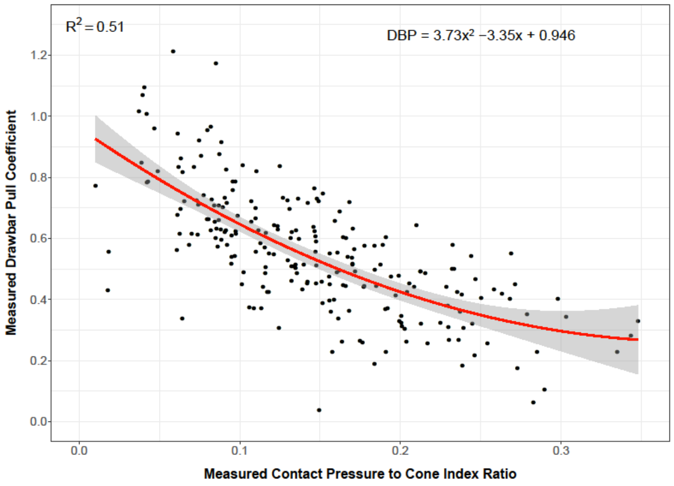


Fig. 5. Drawbar pull coefficient versus the CP to CI ratio for powered tracks (Williams et al., 2019a).

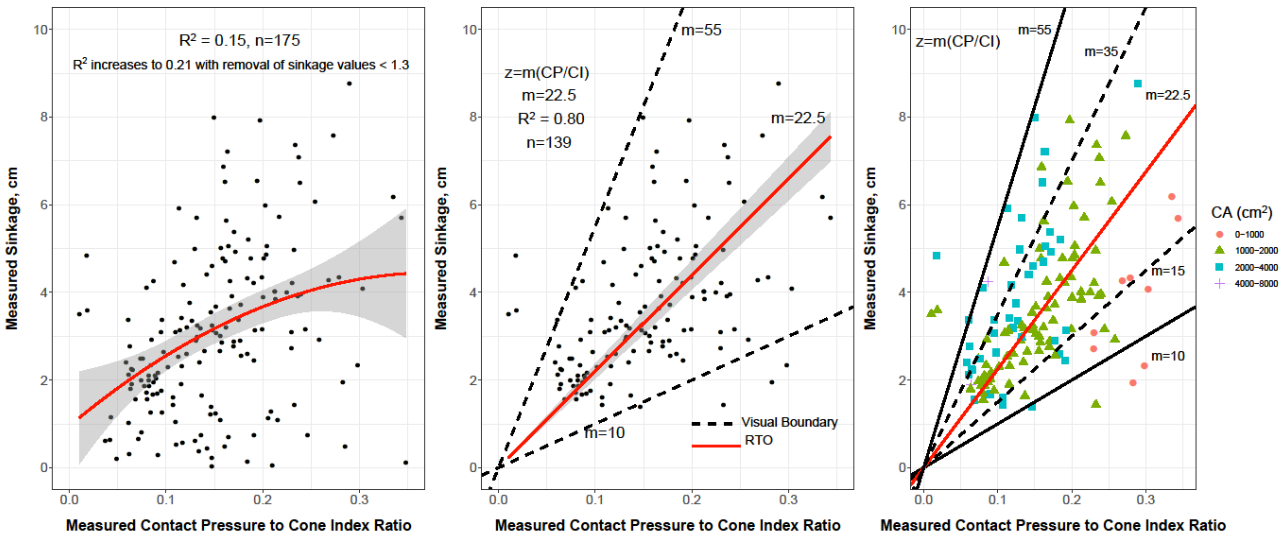


Fig. 6. Relationships for sinkage versus the CP to CI ratio for powered tracks: (a) without forcing through the origin, (b) with regression through the origin, and (c) with regression through the origin and subsets based on contact area (CA) (Williams et al., 2019a).

2.3 DROVE 3.0

Files incorporated as part of the pending DROVE 3.0 (Howard et al., 2019) release originate from the same collection of tracked vehicles tests obtained for the release of DROVE 2.0. The records were scanned and converted into digital spreadsheets in a similar fashion as the previous DROVE releases. Unpublished at the time, the most readily usable information was released as part of DROVE 2.0. This is due to the nature of testing conducted in which the records incorporated as part of DROVE 2.0 were all constant slip test types, whereas, records included as part of DROVE 3.0 also include progressive slip tests. Constant slip tests contain data regarding performance parameters at a single, constant slip coefficient. Progressive slip tests contain performance parameter data for a specific range of slip, with values for each parameter documented at numerous points within the range. As a result, due to the much larger quantity of numerical data included in progressive slip tests, considerably more time and effort was required to convert the records into digital spreadsheets. There was also additional data that was mined for DROVE 3.0 that was not as easily accessible for a variety of different reasons during development of DROVE 2.0. In total, the DROVE 3.0 expansion includes over 400 new data files, some of which provide detailed test progressions that could be useful for numerical modeling development, calibration, or validation. All records are concentrated around testing of tracked vehicles on fine-grained soils, such as high plasticity clay. DROVE 3.0 has prospective implementations in the evaluation and improvement of current mobility models and algorithms.

3. Comparison with Algorithms in the Vehicle Terrain Interface (VTI)

An important aspect of the DROVE releases are its applications to evaluating current predictive algorithms. One set of algorithms that predict vehicle performance over a variety of terrain is the Vehicle-Terrain Interface (VTI) model. The algorithms are contained in a FORTRAN code that calculates performance parameters for a variety of tyres and terrains (Jones et al., 2015). The VTI algorithms are a combination of the waterways experiment station (WES) numeric system (Melzer, 1975) and empirical algorithms similar to those in the NATO reference mobility model (NRMM) (Ahlvin and Haley, 1992). The VTI code provides real-time estimations of vehicle mobility for steered and nonsteered wheels. Jones et al. (2015) details the algorithms used to calculate each parameter.

In order to assess the pre-existing mobility algorithms regarding wheeled vehicles contained in the VTI, the algorithms were compared to measured records from DROVE 1.0 for coarse- (Vahedifard et al., 2016) and fine-grained (Vahedifard et al., 2017) soils. Jones et al. (2015) outlines the algorithms used to calculate each parameter for coarse and fined grained soils.

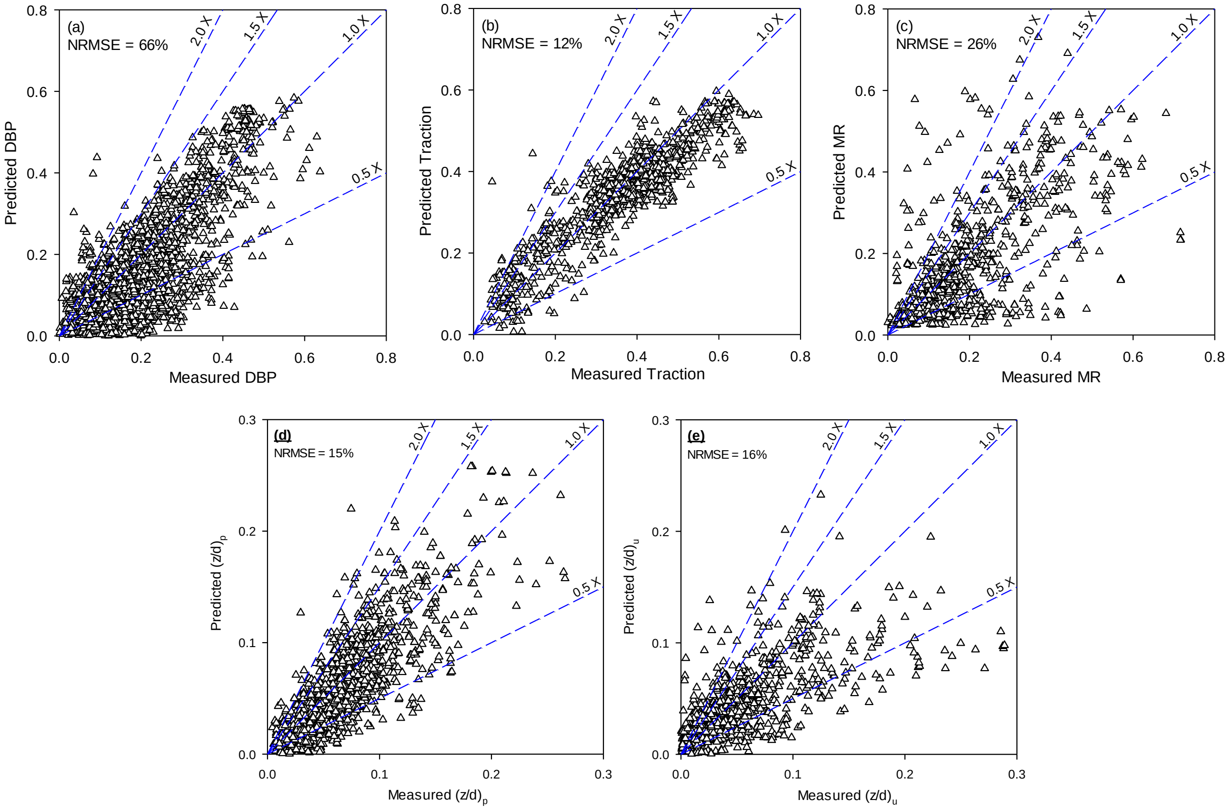


Fig. 7. Relationships between predicted and measured performance parameters sands: DBP, T, MR, $(z/d)_p$, and $(z/d)_u$ for wheels on dry sand in DROVE 1.0 (Vahedifard et al. 2016)

Using DROVE 1.0, Vahedifard et al. (2016, 2017) evaluated the closed form solutions as represented by the VTI model for 5 performance parameters: drawbar pull coefficient (DBP), motion resistance coefficient (MR), traction (T), powered sinkage $(z/d)_p$, and unpowered sinkage $(z/d)_u$ for wheeled vehicles operating on sand (Vahedifard et al. 2016) and clays (Vahedifard et al., 2017). The correlations between predicted and measured DBP, MR, z/d, and T for coarse-grained soils (dry sands) are illustrated in Fig. 7 along with their corresponding normalized root mean square error

(NRMSE) values. In sum there are 3062, 1500, 944, 1362, and 917 data points present for DBP, T, MR, $(z/d)_p$, $(z/d)_u$ and T, respectively. Contour lines are also present to display the amount of data points falling within the regions associated with select slope values.

The results in Fig. 7 demonstrate overall, due to the general trends and corresponding NRMSE values associated with DBP (Fig. 7a) and MR (Fig. 7b), that the variability in the measured data for DBP and MR on coarse-grained soils is not represented very well by the VTI model. Further, with approximately 70% and 60% of the data falling below the line Y=1X for DBP and MR, respectively, the VTI model tends to underestimate values of DBP and MR. For T (Fig. 7c), the trend of the results along with a NRMSE = 12% indicate that range of data represented relatively well by the VTI model. For z/d, it can be deduced that the VTI model tends to better predict z/d for powered vehicles (Fig. 7d) compared to unpowered vehicles (Fig. 7e). It should be noted that no zero or negative values for z/d were used to construct Fig. 7d and 7e.

Similarly, Vahedifard et al. (2017) used the test data wheeled vehicles operating in clay included in DROVE 1.0 to examine the correlations between predicted and measured DBP, MR, T, and z/d. The results are shown in Fig. 8. Totally, there are 869, 498, 634, 701, and 519 data points represented for DBP (Fig. 8a), T (Fig. 8b) MR (Fig. 8c), $(z/d)_p$ (Fig. 8d), and $(z/d)_u$ (Fig. 8e), respectively. Corresponding RMSE and Pearson correlation values along with contour lines displaying the distribution within regions associated with select slope values are also present.

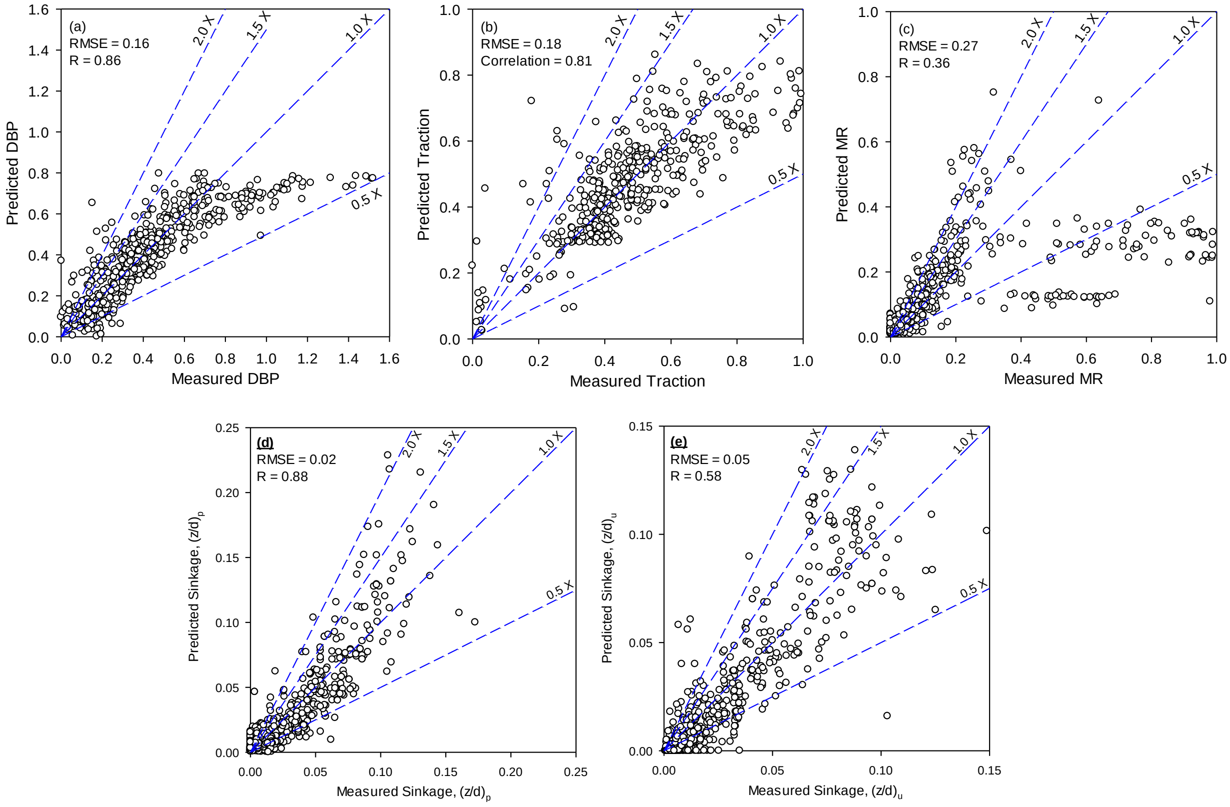


Fig. 8. Relationships between predicted and measured performance parameters: DBP, T, MR, $(z/d)_p$, and $(z/d)_u$ for wheels on clays in DROVE 1.0 (Vahedifard et al. 2017)

The results in Fig. 8e show that the unpowered VTI sinkage performs well when compared to the database developed as part of this study, while the powered equation could be improved (Fig. 8d). The comparison with the VTI DBP algorithm (Fig. 8a) indicate that the VTI model does not accurately represent the measured values in the database with a tendency to under predict once a value of approximately 0.6 is reached. The VTI demonstrated noticeable errors in the calculation of MR (Fig. 8c) and an overall poor correlation and high RMSE to the measurements in the database. The VTI prediction of T (Fig. 8b) seems to provide some level of accuracy, but its reliance on the prediction of motion resistance could introduce meaningful error.

The evaluation of wheeled VTI algorithms for coarse grained soils (Vahedifard et al., 2016) and fine-grained soils (Vahedifard et al., 2017) through the use of DROVE 1.0 revealed the need for improvements to the VTI model, particularly for its predictions for DBP and MR on coarse grained soils and DBP, MR, and $(z/d)_p$ for fine grained soils. In an effort to address this demand various calibration techniques have been applied to develop and validate corrections to be made to the VTI model (Detwiller et al. 2017; Detwiller et al. 2018).

Similar to the evaluation and recalibration process applied to the wheeled VTI model through the use of DROVE 1.0, the same was considered for the tracked VTI algorithms through the use of DROVE 2.0. However, the nature of the VTI equations for tracks poses prominent obstacles to direct application of DROVE records. The primary challenge is that the VTI algorithms for tracked vehicles were developed based on full vehicle system testing which require a set of factors that do not correspond with laboratory dynamometers. These factors include: clearance factor, engine factor, transmission factor, and bogie factor. These factors are used to compute a vehicle cone index, and directly influence the values of the predicted performance parameters.

Though assumptions can be made to select these factors and other required fitting parameters, it is apparent that the VTI was not originally intended to apply fundamental relationships based solely on track parameters and soil strength. This limitation provides a clear area of application of the DROVE fine-grained track data toward development of more fundamentally based performance relationships. Relationships between performance parameters such as DB, MR, T, and z and the CP to CI ratio could be a basis to developing improved predictive equations.

4. Applications and Future Extensions

The evaluation of wheeled VTI algorithms for coarse grained soils (Vahedifard et al., 2016) and fine-grained soils (Vahedifard et al., 2017) using DROVE 1.0 revealed the need for improvements to the VTI model, particularly for its predictions for DBP and MR on coarse grained soils and DBP, MR, and $(z/d)_p$ for fine grained soils. Similarly, for tracked vehicles (Williams et al., 2019), stressed the incompatibility of existing VTI tracked algorithms and pinpoint relationships to be explored in the future using DROVE 2.0. In efforts to address this demand various calibration techniques have been utilized to develop and validate corrections to be made to the wheeled VTI model. The Bayesian calibration techniques applied to coarse-grained soils (Detwiller et al., 2017) and fine-grained soils (Detwiller et al., 2018) observed considerable improvements to the existing VTI model for wheeled vehicles. Specifically, strides were made in the accuracy of the DBP, MR, and T equations coarse-grained soils as well as for all five equations for fine-grained soils. In addition to calibration, other statistical analyses of DROVE 1.0 contents have led to the development of improved predictive algorithms for wheeled vehicles (Mason et al., 2016; 2018; Williams et al., 2017, 2019b).

Future expansion of DROVE is imminent as certain data continues to be obtained from unpublished sources. Also, consideration will be given to compile more data, when available, on soil moisture and temperature of tests. Previous studies clearly demonstrate the effect of soil moisture on off-road ground vehicle mobility (e.g., Stevens et al., 2016; Stevens et al., 2017). However, limitations exist in the physics-based simulation and test records regarding the effects of multi-physics processes (e.g., heat, moisture) in variably saturated soils on off-road ground vehicle mobility. The need is more pronounced considering new patterns of extreme precipitations and drought events under a changing climate (e.g., Leshchinsky et al., 2015; Robinson and Vahedifard, 2016; AghaKouchak et al., 2018; Ragno et al., 2018), which directly affect the terrain behavior.

5. Concluding Remarks

This paper provides an update from a multi-year research program to create and expand the Database Records for Off-road Vehicle Environments (DROVE), DROVE is a suitable asset for the terramechanics community. Providing a consolidated, high-volume dataset comprised of over 8,500 test records spanning across several decades, DROVE contains data regarding the performance of wheeled and tracked vehicles over a variety of terrains. Records contained in DROVE provide opportunity for application in a variety of areas. To date, through comparisons between measured DROVE values and the current VTI models, releases of DROVE have led to applications in, the evaluation, calibration, and simplification of current predictive algorithms for vehicle performance parameters as well as the development of new algorithms.

Acknowledgements

This material is based upon research conducted under contract W9I2HZ-17-C-0021 with the U.S. Army Engineer Research and Development Center (ERDC). The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of ERDC or the U.S. Government. Distribution Statement A: Approved for public release: distribution unlimited.

References

AghaKouchak, A., Huning, L.S., Chiang, F., Sadegh, M., Vahedifard, F., Mazdiyasni, O., Moftakhari, H., Mallakpour, I. 2018. How do natural hazards cascade to cause disasters? Nature, 561(7724), 458-460

Ahlvin, R.B., Haley, P.W., 1992. NATO Reference Mobility Model Edition II, NRMM II User's Guide. Technical Report GL-92-19. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p. 151.

Dettwiller, I. D., Rais-Rohani, M., Vahedifard, F., Mason, G. L., and Priddy, J. D., 2017. Bayesian Calibration of Vehicle-Terrain Interface Algorithms for Loose Sands. Journal of Terramechanics. 71, 45-56.

Dettwiller, I. D., Vahedifard, F., Rais-Rohani, M., Mason, G. L., and Priddy, J. D., 2018. Improving Accuracy of Vehicle-Terrain Interface Algorithms for Wheeled Vehicles on Fine-Grained Soils through Bayesian Calibration. Journal of Terramechanics. 57, 59-68.

Freitag, D.R.,1965. A Dimensional Analysis of the Performance of Pneumatic Tires on Soft Soils. Technical Report No. 3-688. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

Howard, I.L., Griffing, Z., Vahedifard, F., Mason, G.L., Priddy, J.D., 2019. DROVE 3.0: Database Records for Off-road Vehicle Environments, unpublished.

Jones, R.A., McKinley, G.B., Price, S.J., 2015. Algorithms for a Vehicle-Terrain Interface (VTI). Unpublished Technical Report. U.S. Army Engineer Research and Development Center, Geotechnical and Structures Laboratory, Vicksburg, MS.

Kraft, D.C., Luming, H. and Hoppenjans, J.R., 1971a. Multiwheel Landing Gear – Soils Interaction and Flotation Criteria – Phase III Part 1. Technical Report AFFDL-TR71-12. Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory.

Kraft, D.C., Luming, H. and Hoppenjans, J.R., 1971b. Multiwheel Landing Gear – Soils Interaction and Flotation Criteria – Phase III Part 2. Technical Report AFFDL-TR71-12. Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory.

Leshchinsky, B., Vahedifard, F., Koo, H-B., and Kim, S-H., 2015. Yumokjeong Landslide: An Investigation of Progressive Failure of a Hillslope using the Finite Element Method. Journal of Landslides, 12(5), 997-1005.

Mason, G. L., Vahedifard, F., Robinson, J. D., Howard, I. L., McKinley, G. B. and Priddy, J. D., 2016. Improved Sinkage Algorithms for Powered and Unpowered Wheeled Vehicles Operating on Sand. Journal of Terramechanics, 67, 25-36.

Mason, G. L., Williams, J. W., Vahedifard, F., and Priddy, J. D., 2018. A Unified Equation for Predicting Traction for Wheels on Sand over a Range of Braked, Towed, and Powered Operations. Journal of Terramechanics. 79, 33-40.

Melzer, K.J., 1975. Performance of Towed Wheels Operating in Turned Mode on Soft Soil – a Pilot Study. Technical Report M-74. U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, p. 114.

Ragno, E., AghaKouchak, A., Love, C. A., Cheng, L., Vahedifard, F., Lima, C. H. R. 2018. Quantifying Changes in Future Intensity-Duration-Frequency Curves Using Multi-Model Ensemble Simulations. Water Resources Research, 54(3), 1751-1764.

Robinson, J. D., Vahedifard, F. 2016. Weakening Mechanisms Imposed on California's Levees under Multiyear Extreme Drought. Climatic Change, 137(1), 1-14

Stevens, M. T., McKinley, G. B., and Vahedifard, F., 2016. A Comparison of Ground Vehicle Mobility Analysis Based on Soil Moisture Time Series Datasets from WindSat, LIS, and In Situ Sensors. Journal of Terramechanics, 65, 49–59.

Stevens, M. T., McKinley, G. B., and Vahedifard, F. 2017. Full-Featured Ground Vehicle Mobility Analysis using Different Soil Moisture Sources. International Journal of Vehicle Performance, Inderscience, 3(1), 19-35.

Turnage, G.W., 972. Performance of Soils Under Tire Loads Report 8 Application of Test Results to Tire Selection for Off-Road Vehicles. TR 3-666. US Waterways Experiment Station, Vicksburg, MS.

Turnage, G.W., 1995. Mobility Numeric System for Predicting In-the-Field Vehicle Performance Report 1 Historical Review, Planned Development. USACE Waterways Experiment Station, Vicksburg, MS.

Vahedifard, F., Robinson, J.D., Mason, G.L., Howard, I.L. and Priddy, J.D., 2016. Mobility algorithm evaluation using a consolidated database developed for wheeled vehicles operating on dry sands. Journal of Terramechanics. 63, 13-22.

Vahedifard, F., Williams, J.M., Mason, G.L., Howard, I.L., Priddy, J.D., 2017. Development of a Multi-Year Database to Assess Off-Road Mobility Algorithms in Fine-Grained Soils. International Journal of Vehicle Performance. 3(1), 3-18.

Williams, J.M., Vahedifard, F., Mason, G.L., Howard, I.L., Borazjani, A., Priddy, J.D., 2017. Expansion and Application of Database Records for Off-Road Vehicle Environments (DROVE). Proc. of the AVT-265 Research Specialists Meeting on Integrated Virtual NATO Vehicle Development, Vilnius, Lithuania, May 15-17, Paper 13, pp. 10.

Williams, J.M., Vahedifard, F., Howard, I.L., Borazjani, A., Mason, G.L., Priddy, J.D., 2019a. Mobility Guidance for Tracked Vehicles on Fine-Grained Soil from Historical Full-Scale Test Data in DROVE 2.0. Journal of Terramechanics. 84, 1-12.

Williams, J.M., Vahedifard, F., Mason, G.L., Priddy, J.D., 2019b. New Algorithms for Predicting Longitudinal Motion Resistance of Wheels on Dry Sand. Journal of Defense Modeling & Simulation: Applications, Methodology, Technology. 16(3), 283-295.

Wismer, R.D. 1966. Performance of Soils under Tire Loads Report 3. TR-3-66. US Waterways Experiment Station, Vicksburg, MS.