

Review Article

A REVIEW OF SOIL DYNAMICS IN TRACTION STUDIES

Abstract

As the world population increases more than ever before and increasing demand on food, feed and fiber, and security, the number of off-the-road vehicles is rapidly increasing for agriculture, forestry, military, mining and construction industries. Many researchers have studied and still investigating traction as it relates off-road vehicles and publications abound especially from developed countries of Europe, America and others. In our generation scientists are trying to put robotic vehicles on the lunar and Martian terrains. This trend makes the study of soil dynamics in traction a sine qua non in our tertiary and research institutions. In Nigeria there is a dearth of publications in this specialized area of study. This is a review paper and the purpose is to highlight some of the studies that have been conducted over the years, with a view to enlightening, encouraging, stimulating and challenging would be researchers. Trends in the development of soil bin with single wheel testers were reviewed including tractive and transport devices used in them. Traction parameters including motion resistance, measurement and data acquisition systems, traction predictive equations including wheel numeric and mobility numbers were also reviewed. Efforts made in the development of soil bin for soil dynamics research and further research interest at the Federal University of Technology, Akure (FUTA) were highlighted.

Keywords: soil dynamics, traction, motion resistance, traction parameters, prediction equations

1. Introduction

To an agricultural engineer soil may be defined as a loose (unconsolidated) heterogeneous three-phase mineral or organic matter surface of the earth's crust that is capable of supporting growth of plant. Foth (1984) defines soil as unconsolidated mineral matter on the surface of the earth that has been subjected to and influenced by genetic and environmental factors of parent material, climate (including moisture and temperature effects) micro and macro-organisms and topography, all acting over a period of time and producing a product-soil that differs from the material from which it is derived in many physical, chemical and biological properties and characteristics. According to Culpin (1986), agricultural soils consist mainly of a heterogeneous collection of mineral particles existing either singly or as small 'crumbs'

32 comprising several particles grouped together. Between soil particles are spaces which may be
33 filled by air or by water.

34 Due to the high and increasing global population, the demand for more food feed and fiber will
35 continue to be on the increase. This demand will call for higher level of agricultural
36 mechanization and corresponding increase in size of agricultural machinery. Increasing weight of
37 agricultural machinery is not without its negative side effects which is soil compaction. Soil
38 compaction retards crop germination, growth and yield. It decreases water infiltration into the
39 soil and increases surface water runoff and erosion. This type of soil degradation is also common
40 with the use of forestry machinery and off- the road military equipment. In order to make the soil
41 serve man sustainably, the study of soil dynamics in traction is *sine qua non*.

42 Terrain may be defined as a stretch of land, especially with regard to its physical and/or natural
43 features. Traction can also be defined as the ability of vehicle's tractive element to generate
44 enough forces/thrust to overcome all types of vehicle resisting forces and hence keep the vehicle
45 in constant travel (Yong *et al.*, 1984). The study of interaction of terrain with machine usually
46 called soil-machine interaction can be classified into two (Ani *et al.*, 2014): interaction of the soil
47 and the tractive element e.g. wheel or track; interaction of the soil with tools e.g. tillage tools,
48 planters, fertilizer applicators, harvesting tools and other soil-engaging tools. The first is known
49 as traction studies while the second is called tillage studies. In traction studies, interaction
50 between vehicle and terrain is achieved through the running gear system, which produces
51 reaction and responses at the terrain interface. The greater the ability of the terrain material and
52 the interactions at the interface to transfer the thrust action into the substrate, the better the
53 capacity of the vehicle to achieve maximum tractive efficiency (Yong *et al.*, 1984).

54 For optimum mobility to occur, it is required that the vehicle be able to move from one point to
55 another with minimum amount of motion loss and energy input. To achieve this, the terrain must
56 provide floatation as well as resistance capability such that enough thrust can be developed
57 between the running gear contact element and terrain material itself with minimal wheel
58 slippage.

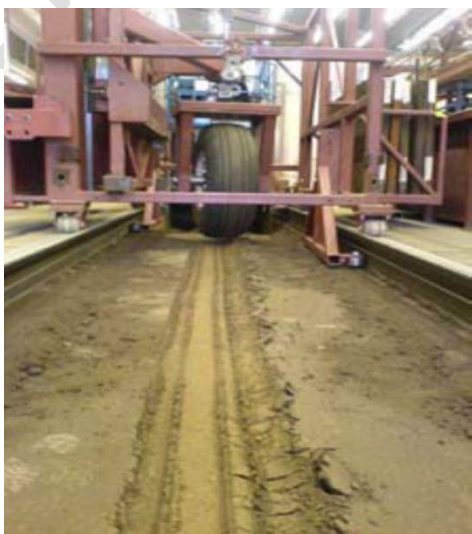
59 Soil dynamics in traction is significant in all off-road vehicles soil- wheel interaction both for
60 Agriculture, Forestry and Military off- road vehicles. According to Zoz and Grisso (2003), the
61 basic problems and concerns in the study of vehicle traction mechanics revolve around the need
62 to: establish a better knowledge and insight into the mechanics of interaction between vehicle
63 tractive elements and the material surface over which they act; develop a rational means for
64 evaluating the performance of the tractive elements over specific terrain conditions; provide the
65 mathematical or computational models of performance of the tractive elements thus leading to
66 implementation of optimization procedures; establish the basic means for determination of the
67 capability of a vehicle to move from one location to another. The major goal of researcher in the
68 field of off-road traction mechanics as it applies to agricultural field operation is to understand
69 and predict the performance of tractors. Zoz and Grisso (2003) reported that tractor performance
70 is influenced by traction elements, soil conditions, implement type and tractor configuration and
71 that efficient operation of farm tractors includes: maximizing the fuel efficiency of the engine
72 and drive train; maximizing the tractive advantage of the tractive devices and selecting an
73 optimum travel speed for a given tractor-implement system. The understanding and prediction
74 of tractor performance has been a major goal of many researchers. Tractor performance is
75 influenced by traction elements, soil conditions, implement type, and tractor configuration
76 (Brixius, 1987).

77

78 2. Developments in Traction Soil Bins and Single Wheel Testers

79 Freitag (1968) studied the performance of pneumatic tires on sand. The tire-soil tests were
80 conducted with single-wheel dynamometer and soil-bin system in the facilities of the Mobility
81 Research Branch of the U.S. Army Engineer Waterways Experiment Station (WES). Upadhyaya
82 et al. (1986) developed a unique, mobile, single wheel traction testing device at the Department
83 of Agricultural Engineering, University of California, Davis. It was essentially a mobile soil bin
84 that could be used to conduct controlled field experiments in situ. The device was used to test
85 tires ranging in diameter from 0.46 m (rim ID) to 2 m (OD) and up to maximum tire width of 1.0
86 m. The system was designed to provide an infinitely variable vertical load up to a maximum of
87 26.7 kN and a draft load up to a maximum of 13.3 kN.

88 Patel and Godwin (2008) carried out a study on controlled soil bin tests for pneumatic tires. In
89 the study, a single wheel test bed (Figure 1) was developed for performing wheel-soil interaction
90 study at heavy wheel loads under controlled environment. The tests were performed on soft and
91 hard surfaces characterized by soil and concrete respectively on the soil bin.



92

93 Figure 1. Off road dynamic facility – soil bin (Source: Patel and Godwin, 2008)

94

95 Yahya et al. (2007) carried out a study on a long soil bin to study tire traction facility (Figure 2).

96 This study spearheads fundamental research on traction mechanics with high-lug agricultural

97 tires on tropical soils was designed and developed. The developed facilities consist of a moving

98 carriage with a cantilever-mounted tire that moves in either forward or reverse directions on wall

99 rails above a soil tank. The facility set-up was able to operate in either: (a) towing test mode for

100 tire motion resistance studies or (b) driving test mode for tire net traction and tractive efficiency

101 studies. The test tire on the moving carriage under the towing test mode was to operate and

102 engage onto the soil surface in the tank through a chain drive system. Under the driving test

103 mode, the test tire on the moving carriage was powered to rotate by a motor and a gearbox

104 system with an additional pull provided by a cable-pulley mechanism connected to a tower with

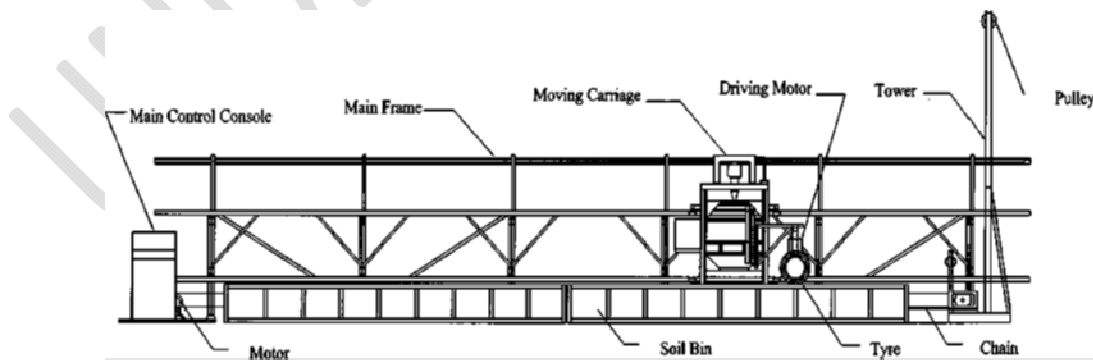
105 hanging dead weights. The long soil bin however results in testing high lug agricultural tires at

106 towed and driving modes for their motion resistance, net traction and tractive efficiency at

107 different soil conditions. The facility can also be used for testing the effects of other parameters

108 such as dynamic loading, ballasting and travel speed and tire inflation pressure on tractive

109 performances of the tire.

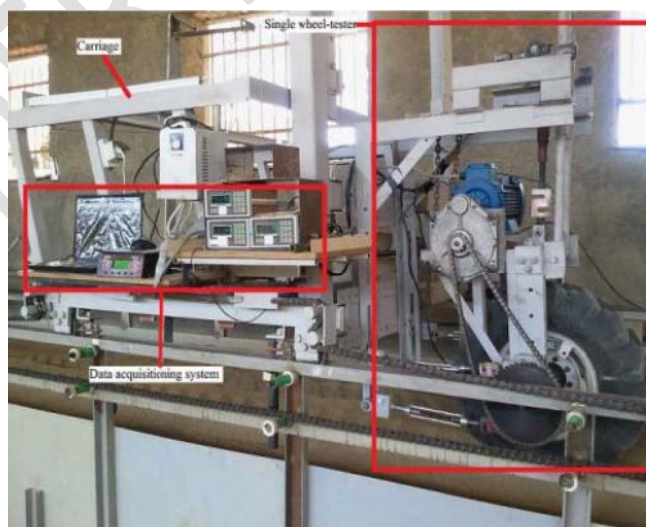


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111 Figure 2. Schematic diagram of a long soil bin for tire traction testing facility (Source: Yahya *et al.*, 2007)

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113
114 Taghavifar and Mardani (2012) carried a study on contact area determination of Agricultural
115 tractor wheel with soil. In the study, an experimental test was conducted inside a soil bin facility
116 providing entirely reliable and controlled condition for the test. The test had the advantage of
117 utilizing images taken of the contact areas and subsequently, using a planimeter to obtain the
118 values of contact area precisely. Test variables that were the two most prominent and influential
119 parameters were tire inflation pressure and vertical load applied on wheel. Similarly, Taghavifar
120 and Mardani (2014) carried out a study on evaluation and measurement of the performance
121 parameters of agricultural wheels. In the study, a single-wheel tester (Figure 3) was designed,
122 constructed and evaluated inside a soil bin. The tested wheel was directly driven by the electric
123 motor. Vertical load was applied by a power bolt on wheel. This tester could measure required
124 draft force, the depth of tire sinkage, contact area between wheel and soil, and soil stress at
125 different depths both alongside and perpendicular to the direction of traversing. In order to
126 evaluate the system performance, traction force was measured by the connected S-shaped load
127 cell at arms between the wheel-tester and carriage.



128
129 Figure 3. The General Overview of the Testing Facility (Source: Taghavifar and Mardani 2014)
130

131 Ahmad et al. (2011) reported a motion resistance rig (Figure 4) that was designed to measure the
 132 towing force of a single test wheel towed by a tractor. Taghavifar and Mardani (2015) reported
 133 on single wheel tester (Figures 5 and 6) at the Department of Agricultural Machinery of Urmia
 134 University, Iran to study the effects of slippage, velocity and wheel load on net traction.

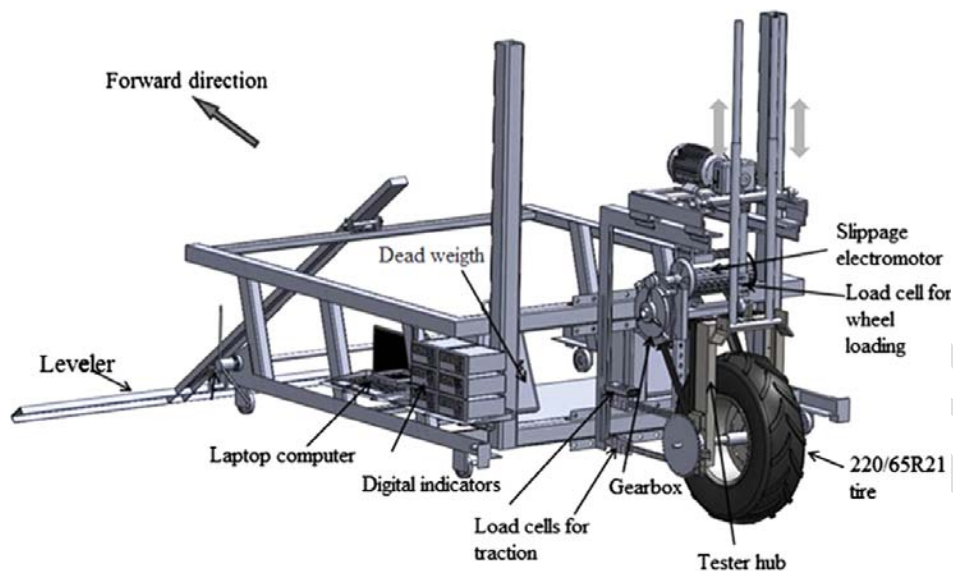


135
 136 1. Test wheel 2. Load hanger 3. Load 4. The BFG 5. Three-point hitch frame
 137 6. Connecting cable 7. Notebook PC

138 Figure 4. Test rig coupled to the tractor during field test (Source: Ahmad *et al.*, 2011)



139
 140 Figure 5. General view of a single-wheel tester inside soil bin facility (Source: Taghavifar and Mardani,
 141 2015)



142

143 Figure 6. Schematic of the utilized single-wheel tester along with its detailed components
 144 (Source: Taghavifar and Mardani, 2015).

145

146 Some other single wheel testers in the soil bins and in the field are presented in Table 1.

147 Table 1: Some Single wheel Tester used in Soil bins and in the field (a) In Soil bins (b) In the
 148 field

Institution	Range of wheel diameter (mm)	Max dynamic load, kN	References
USDA-ARS-NSDL (Auburn, Alabama)	1265 - 1880	44	Burt <i>et al.</i> , 1980; Lyne <i>et al.</i> , 1983; Way, 2007
University of Kentucky, Lexington, Ky	- 745 max.	9.8	Wood and Wells, 1983; Wells and Buckles, 1987; Rohlf <i>et al.</i> , 1994; Wells <i>et al.</i> , 1996.
Carleton University, Ottawa, Ontario, Canada	- 1200	11.2	Wu, 2000
Technical University of Munich, Munich, Germany	500 -1200	Using Dead	Krick, 1973

		weights	
Cranfield University at Silsoe, Silsoe Bedfordshire, U. K	500 - 1400	123 Through hydraulic cylinders	Godwin <i>et. al.</i> , 2006
(b) Single wheel Tester used in the field			
USDA-ARS-NSDL (Auburn, Alabama	1261 - 2180	66	Way, 2007
University of California, Davis	460 - 2500	27	Upadhyaya <i>et al.</i> ,1986
Silsoe Research Institute, Silsoe Bedfordshire, U. K	1200 - 1760	27	Dwyer, 1972, 1985; Billington, 1973
DERA (QinetiQ Ltd) Farmborough, Hampshire, U.K	-- --	55 Using Dead weights	Maclaurin, 1981, 1984.
Technion- Israel Institute of Technology, Haifa, Israel	-- 2000	50	Ronai <i>et al.</i> , 1994 a, b

149

1503. Motion Resistance and Measurement

151 According to Ahmad et al. (2011), motion resistance can be regarded as the total drag opposite
 152 to the steady motion of a free motion wheel across a horizontal surface. To them, it can also be
 153 defined as integral of the horizontal component of the radial stresses. Motion resistance refers to
 154 the resistance to motion of a wheel caused by the absorption of energy in the contacting surfaces
 155 of the wheel and the soil upon which the wheel rolls. The motion resistance may be expressed as
 156 reported by Ahmad et al. (2011) in Eq. (1).

$$157 \quad MR = MR_c + MR_b + MR_t \quad (1)$$

158 The total motion resistance force, MR is made up of the MR_c , the component due to soil
159 compaction, MR_b , the component due to horizontal soil displacement and MR_t , the component
160 due to flexing of the tire. For vehicle operating on a hard surface, MR_t , constitutes the largest
161 percentage of the motion resistance force and this, can be slightly reduced by increasing the
162 inflation pressure and the effective stiffness of the tire. In off-road situations, however, the
163 components MR_c and MR_b make up the largest proportion of the motion resistance force and
164 increasing the inflation pressure and the tire stiffness have shown to increase the motion
165 resistance Plackett (1985).

166 Usually, the motion resistance is expressed in terms of motion resistance ratio (τ).
167 Mathematically, the motion resistance ratio is as expressed as shown in Eq. (2).

$$168 \quad MMR(\tau) = \frac{MR}{W} \quad (2)$$

169 where MR is the motion resistance force suffered by the wheel and W is the normal load on the
170 wheel.

171 The performance characteristics of a towed wheel are described usually by a towing force
172 (motion resistance), sinkage and skid. The most pertinent parameter of the towed pneumatic
173 wheel is the motion resistance, which is influenced by the tire design, system parameters and
174 terrain characteristics. In studying the soil-wheel interaction, the behavior of the soil and the
175 most important design parameters of the wheel form the basic inputs (Pandey and Tiwari 2006).

176 Traditionally, design parameters of the tire include diameter of the wheel, section width, section
177 height, inflation pressure and load deflection relationship. All these are considered to have
178 varying degree of influence on the tire soil interaction. The terrain characteristics include the
179 types of soil, soil moisture content and its compaction level and the system parameters comprise

180 the dynamic (normal) load on the wheel and forward speed. The dynamometer reading is usually
181 always taken to determine the towing force.

182

183

1844. **Traction**

185

186 Traction may be defined as the force derived from the interaction between a device and a
187 medium that can be used to facilitate a desired motion over the medium (Gill and VanDen Berg,
188 1968). Net traction, can be defined (ASAE S296.5 2009) as the force parallel to the direction of
189 travel, developed by the traction device and transferred to the vehicle. Gross Traction is the sum
190 of net traction and motion resistance.

191 Tractive effort developed by off-road vehicles has been of interest to people engaged in
192 agricultural, forestry, military and mining operations. Most research conducted in off-road
193 traction mechanics has focused on either agricultural or military equipment (Persson, 2009)

194 Tractive performance is affected by both the soils' normal strength and its shear strength. In
195 general, normal strength has the most effect on motion resistance, while shear strength has the
196 most effect on travel reduction. Describing and documenting the soil is perhaps the most difficult
197 part of traction testing. There are several reasons for the difficulty. First, the soil has sufficient
198 variation, which can easily influence the soil sampling device. Second, soil measurements are
199 time consuming, and finally, the sampling technique may not be replicated or repeated for
200 different soil conditions. For this reason, much of the traction tests reported are of a comparative
201 nature, that is, one traction device compared to another device while operated under the same
202 soil conditions. The device that is the most portable and commonly used, the cone penetrometer,
203 works well only if the soil has moisture and if it has not been disturbed. Soil strength as
204 measured by the soil cone penetrometer provides a combined measurement of soil normal

205 strength and shear strength. The cone penetrometer also requires a large number of
206 measurements because there is a large variability in the test results.

207 **4.1 Traction Parameters**

208 According to Zoz and Grisso (2003), five dimensionless parameters are used to describe
209 tractive

210 performance:

- 211 • Travel reduction ratio (TRR), commonly called "slip" and expressed in percent.
- 212 • Net traction ratio (NTR), sometimes called pull/weight ratio.
- 213 • Tractive efficiency (TE) usually thought of as percent but used as a ratio in this paper.
- 214 • Gross traction ratio (GTR).
- 215 • Motion resistance ratio (MRR).

216 The traction parameters involving forces are all normalized by dividing by W_d , the dynamic
217 force reaction supporting the wheel or traction device. W_d includes static axle weight and any
218 weight transfer that might take place during the testing process, that is, the total reaction force.
219 Dividing by W_d allows comparisons between tires and other tractive devices of different sizes
220 and weights and provides a dimensionless parameter for traction comparisons. It is important to
221 note that the above parameters apply to a traction device and not necessarily to a vehicle (Zoz
222 and Grisso, 2003).

223

224 **5. Measurement and Data Acquisition**

225 Data acquisition and control computers and all the associated recording and display equipment
226 are required to process data acquired during the conduct of test programs. In addition to
227 coordinating data acquisition, the package may also provide computer control of the test units.

228 For effective work and utilization of soil bin in traction studies, commercially available
229 measuring and recording equipment should be used where necessary. It is expected that as
230 measurable parameters are identified, new measuring devices should be developed so that their
231 importance in soil machine - relations can be determined by physical measurements. Direct
232 access to instrument manufacturers, who share in the development of new measuring devices,
233 provides an effective way of securing best designs. An overall goal of soil dynamics will permit
234 manipulation of soil from an initial known condition into a new and specified condition; digging,
235 cutting, loading and transport of soil in effective and efficient ways; attainment of adequate
236 tractive forces in effective and efficient manners; mobility across terrain with a variety of
237 conditions; and prediction of soil behavior under the action of dynamic loads applied by
238 machines and vehicles (Upadhyaya, 1994).

239 The Data acquisition system for the test facility is usually located on a special place on the
240 carriage close to the soil bin facility. This dedicated system is made up of some sensor outputs
241 interfaced to a computer system. The computer system can receive, monitor, display and store
242 the measured signals from the respective transducers. A program is used to retrieve and read
243 the stored data and compute average, standard deviation and variance of the needed tire
244 performance measurements. An optic tachometer that is located on the main drive shaft of the
245 carriage driving unit measures the moving carriage speed. This unit can detect revolutions in
246 digital values without making direct contact. In detecting revolutions, the optic tachometer
247 senses the special color sign that is located on the revolving shaft and detects signals equals to

248 the numbers of the revolution of the rotating main drive shaft. A notebook may be used for data
 249 acquisition system, monitoring and real time control of the system. In any mode, data
 250 acquisition system may perform at different sampling rates. The display of data is available to
 251 user at real time on the computer monitor screen and the data could be permanently stored in a
 252 defined file in the computer (Mardani *et al.*, 2010).

2536. Traction Prediction Equations

254 According to Upadhyaya (2009) numerous attempts have been made to quantify soil-traction
 255 device interaction. These attempts can be classified under the following three broad categories:
 256 (1) analytical methods; (2) semi-empirical, parametric or analog methods; and (3) empirical
 257 methods.

258 **6.1 The analytical or theoretical approach** assures a certain level of understanding of the basic
 259 process (Freitag, 1985). In order to predict the performance of a traction device, we need to
 260 know the distribution of normal and shear stress at the soil-tire/track interface and the geometry
 261 of the 3-D contact surface. Wulfsohn (2009) has provided an extensive review of soil-wheel
 262 interaction surface geometry and distribution of stresses at the soil-traction device interface.

263 **6.2 The semi-empirical or parametric approach** utilizes two analog devices to represent soil-
 264 traction device interaction. Vertical deformation of the soil under load is assumed analogous to
 265 soil deformation under a flat plate. The shear deformation of the soil under a traction device is
 266 assumed to be similar to the shear due to a torsional shear device or a rectangular grouser unit.
 267 The normal stress under a flat plate is assumed to be of the form (Bekker, 1960 and Wong,
 268 1984):

$$269 \quad P = \left(\frac{K_c}{b} + K_\phi \right) z^n \quad (3)$$

270 where P is normal pressure under the plate, b is minimum dimension of a rectangular plate; the
 271 diameter for a circular plate, z is soil deformation and K_c , K_ϕ and n are soil parameters
 272 Although several different expressions are available to relate shear stress to soil deformation
 273 (Bekker, 1960, 1969; Yong *et al.*, 1984), the Janosi and Hanamoto (1961a, b) relationship is
 274 most widely used in agriculture:

$$275 \quad \tau = \tau_{\max} \left(1 - e^{-j/k} \right) \quad (4)$$

276 where τ is shear stress,

277 $\tau_{\max} = c + p \tan \phi = \text{max shear stress}$,

278 $\tau_{\max} = c + \sigma \tan \phi = \text{max shear stress}$

279 c is cohesion, σ is normal stress, ϕ is soil internal friction angle, j is shear deformation and k is
 280 shear modulus.

281 It was reported (Upadhyaya, 2009) that:

$$282 \quad Z_0 = \left[\frac{P_{gr}}{K_c/b + K_\phi} \right]^{1/n}$$

$$283 \quad MR = \frac{bp_{gr}^{(n+1)/n}}{(n+1) \left[\frac{K_c}{b} + K_\phi \right]^{1/n}} \quad (5)$$

284 Where Z_0 is maximum deformation, p_{gr} is average ground pressure equal to $p_c + p_i$, p_c is pressure
 285 due to carcass stiffness, p_i is tire inflation pressure and MR is motion resistance.

286 Reece (1964) modified Eq. (3) to make it dimensionally more consistent. Reece's equation is as
 287 follows:

$$288 \quad P = \left(cK'_c + \gamma bK'_\phi \right) \left(\frac{Z}{b} \right)^n \quad (6)$$

289 where $K'c$, $K'\phi$, n = dimensionless constants and γ = weight density of soil. Upadhyaya et al.
 290 (1993) found that predictions based on this equation were more consistent with their field data
 291 than were predictions made using Eq. (3).

292 According to Goering et al. (2006), this approach has been useful for explaining some aspects of
 293 tractive device-soil interaction; however, semi-empirical approach has limited practical
 294 application.

295 **6.3 Empirical Approach.** This approach evolved at the end of World War II as a means of
 296 measuring trafficability of soil at the U.S. Army Corps of Engineers Waterways Experiment
 297 Station (WES). It was intended for quick numerical evaluation of soil in the field (Upadhyaya,
 298 2009). It is based on soil cone index as the only soil strength parameter. On the basis of
 299 numerous tests conducted at WES, primarily on fine-grained wet clay soil and coarse-grained dry
 300 Yuma sand, vehicle cone index (VCI) was developed to determine a “go-no go” criterion for
 301 military vehicles (Freitag, 1985; Wong, 1989). The VCI was based on measured soil cone index
 302 values. Goering *et al.* (2006) reported that empirical methods using field and/or soil bin
 303 laboratory tests of traction devices either by themselves or as part of a complete vehicle are the
 304 most used technic for assessing tractive performance by both vehicle and traction device
 305 manufacturers.

306 Several empirical equations for traction prediction have been developed by researchers. Wismer
 307 and Luth (1973) developed a traction prediction equation for a single powered wheel. The
 308 equation is an exponential function of travel reduction and is rewritten (Eq. 7) as:

$$309 \quad NTR = \frac{P}{W} = 0.75 \left(1 - e^{(-0.3C_n S)} \right) - \left(\frac{1.2}{C_n} + 0.04 \right) \quad (7)$$

310 Where NTR is net traction ration, P is net wheel pull, W is dynamic wheel load, C_n is wheel
 311 numeric,
 312 ($C_n = C.I.d.b/W$), CI is soil cone index, d is unloaded tire diameter, b is unloaded tire width and S
 313 is travel reduction (fraction). Wheel numeric is a simplified wheel-soil contact model based on
 314 dimensionless parameters. Wismer and Luth also derived an equation for predicting the motion
 315 resistance ratio, which is the last expression of (Eq.7):

$$316 \quad MRR = \frac{1.2}{C_n} + 0.04 \quad (8)$$

317 Where MRR is the motion resistance ratio, which is the ratio of the wheel motion resistance to
 318 the dynamic wheel load. The traction equation given by Gee-Clough et al. (1978) takes a similar
 319 form as that developed by Wismer and Luth (1973) to model mobility number, M . The equation
 320 is of the form (Eq. 9):

$$321 \quad M = \frac{CIdb}{W} \left(\frac{\delta}{h} \right)^{0.5} \left[\frac{1}{1 + \frac{b}{2d}} \right] \quad (9)$$

322
 323 where M is mobility number, δ is tire deflection and h is tire section height. The mobility
 324 includes wheel numeric used by Wismer and Luth. Mobility number is used to predict the
 325 combined effect of soil-wheel parameters on the tractive performance.

326 Brixius (1987) presented traction prediction equations for single bias ply tires. His equations
 327 were revisions of equations developed by Wismer and Luth (1973). The equations are rewritten
 328 as:

$$\frac{GT}{W} = 0.88(1 - e^{(-0.1B_n)})(1 - e^{(-7.5S)}) + 0.04 \quad (10)$$

$$MRR = \frac{1}{B_n} + 0.04 + \frac{0.5S}{B_n^{0.5}} \quad (11)$$

Where GT is gross traction and B_n is called mobility number defined by Brixius as (Eq. 12):

$$B_n = \frac{CI db(1 + 5\delta/h)}{W(1 + 3b/d)} \quad (12)$$

These and several other researchers have reported several models for wheel numeric, motion resistance ratio and mobility number.

7. Development of Soil bin at FUTA and Future work

Some efforts have been made to conduct research in soil dynamics in tillage at the department of Agricultural and Environmental Engineering of FUTA. The department has developed both indoor and outdoor soil bins (Figs. 7 – 9) and various studies have been reported (Manuwa, 2002; Manuwa and Ademosun, 2007; Manuwa, 2009; Manuwa and Ajisafe, 2010; Manuwa *et al.*, 2011; Ajewole and Manuwa, 2014a, b). Further work is in progress in soil dynamics in tillage and traction. Single wheel tester is being developed for another indoor soil bin in the Soil dynamics laboratory. Terrain characterization is also an area of study we need to research into.



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351

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Figure 7. An indoor soil bin at FUTA (Manuwa and Ademosun, 2007)



353

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Figure 8. Indoor Soil bin (FUTA) with overhead gantry crane (Manuwa and Ajisafe, 2010)



355

356

Figure 9. Outdoor soil bin at FUTA (Manuwa *et al.*, 2011)

357

358 8. Conclusions.

359 Soil dynamics in traction has been reviewed with the aim of enlightening, motivating and
360 challenging would-be researchers in the specialized field. It is noted that although a lot of
361 research has been done by researchers in developed countries, however there is a dearth of
362 publication from Nigerian researchers.

363 Some efforts have been made by researchers at FUTA to study soil dynamics in tillage and more
364 efforts are required to intensify studies in traction which they have embarked upon.

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368 REFERENCES

369

370 Ajewole, P.O. and Manuwa S. I. (2014a). Development of Equipment for Measuring Pressure-
371 Sinkage Behaviour of a Heavy Clay Soil. Proceedings of 2014 International Soil Tillage
372 Research Organisation (ISTRO) Nigeria Branch, held at the FUTA Hilltop Auditorium,
373 Akure, Ondo State Nigeria, November 3 - 6, 2014. Pp. 84 – 93

374 Ajewole, P. O. and S. I. Manuwa (2014b). Establishment of Bekker's Model for Predicting
375 Pressure-Sinkage Behaviour of Loamy Sand Soil. 2014 Proceedings of the 15th
376 International Conference and 35th AGM of the Nigeria Institution of Agricultural
377 Engineers (NIAE), held at the FUTA Hilltop Auditorium, Akure, Ondo State Nigeria
378 September 22 - 26,

379 Ahmad, D., Shamsuddin, S., Fashina, A. B., and Akande, F. B. (2011). Development of a tractor-
380 pulled motion resistance test rig for traction studies on towed narrow wheels, 4(4), 21–27.
381 <http://doi.org/10.3965/j.issn.1934-6344.2011.04.021-027>

- 382 Ani A.O., Uzoejinwa B.B., Ezeama A.O., Ugwu S.N., Ohagwu C.J and Odigbo E.U (2014) Soil
383 Bin Facility for Soil-machine Interaction Studies. Proceedings of the International Soil
384 tillage Research Organisation pg 110 – 124
385
- 386 ASAE S296.5 (2009). General Terminology for Traction of Agricultural Traction and Transport
387 Devices and Vehicles. ASAE Standards. American Society of Agricultural and Biological
388 Engineers, St. Joseph MI.
389
- 390 Bekker M. G. (1960). Off the road locomotion. University of Michigan Press, Ann Arbor
391
- 392 Bekker, M. G. (1969). *Introduction to Terrain-Vehicle Systems*. Ann Arbor, Michigan.:
393 University Michigan Press.
- 394 Billington, W. P.(1973). The N.I.A.E. Mk II single wheel tester. *J. Agric. Eng. Res.* 18: 67-70
395
- 396 Brixius, W. W. (1987). Traction prediction equations for bias-ply tires. ASAE Paper No. 871622.
397 St. Joseph, Mich.: ASAE.
398
- 399 Burt, E. C., C. A. Reaves, A. C. Bailey, and W. D. Pickering. (1980). A machine for testing
400 tractor tires in soil bins. *Trans. ASAE* 23(3): 546-547, 552.
401
- 402 Culpin, C. (1986). *Farm Machinery*. 11th Edition English Language Book Society/Collins,
403 London.
404
- 405 Foth, H.D. (1984). *Fundamental of Soil Science*. 7th Edition. John Wiley and Sons. New York.
406
- 407 Gee-Clough, D., M. Mcallister, G. Pearson and D.W. Evernden. (1978). The empirical prediction
408 of tractor implements field performance. *Journal of Terramechanics*. 15(2):81-94.
409

- 410 Dwyer, M. J. (1972). Field measurement of agricultural tyre performance at the National
411 Institute of Agricultural Engineering. In *Proceedings 4th International Conference*
412 *ISTVS*, 39-60. Hanover, N.H.: ISTVS.
- 413
- 414 Dwyer, M. J. (1985). Predicting tractive performance. In *Proceedings International Conference*
415 *on Soil Dynamics*, 4: 679-692. Auburn, Ala: Auburn University.
- 416
- 417 Freitag, D. R. (1968). Dimensional Analysis of Performance of Pneumatic Tires on sand.
418 *Transactions of the ASAE* 11(15):669 - 672
- 419
- 420 Freitag, D. R. (1985). Soil dynamics as related to traction and transport systems. In *Proceedings*
421 *International Conference on Soil Dynamics*, 4: 605-629. Auburn, Ala.: Auburn
422 University.
- 423
- 424 Gill, W. R. and Vanden Berg, G. E. (1968). Soil dynamics in tillage and traction. Handbook 316,
425 Agricultural Research Service, U. S. Department of Agriculture, Washington, D. C.
- 426
- 427 Godwin, R. J., J. L. Brighton, K. Blackburn, T. E. Richards, D. Ansorge, and P. N. Wheeler.
428 (2006). Off-road dynamics research at Cranfield University at Silsoe. ASABE Paper No.
429 06-1131. St. Joseph, Mich.: ASABE.
- 430
- 431 Goering C. E., Stone M. L., Smith D. E. and Turnquist P. K. (2006). Off-road Vehicle
432 Engineering Principles. American Society of Agricultural and Biological Engineers, 351-
433 379
- 434
- 435 Janosi, Z. and B. Hanamoto. (1961a). An analysis of the pull vs. slip relationship for track laying
436 vehicles. Report No. 69. Warren, Mich.: Land Locomotion Laboratory.
- 437
- 438 Janosi, Z. and B. Hanamoto. (1961b). An analytical determination of drawbar pulls as a function
439 of slip for tracked vehicles in deformable soils. Paper No. 41 in *Proceedings of the 1st*
440 *International Conference on the Mechanics of Soil-Vehicle Systems*. ISTVS.

- 441
442 Krick, G. (1973). Behaviour of tyres driven in soft ground with side slip. *J. Terramechanics* 9(4):
443 9-30.
444
- 445 Lyne, P. W. L., E. C. Burt, and J. D. Jarrell. (1983). Computer control for the NTML single
446 wheel tester. ASAE Paper No. 83-1555. St. Joseph, Mich.: ASAE
447
- 448 Maclaurin, E. B. (1981). The effect of tread pattern on the field performance of tyres. In
449 *Proceedings 7th International Conference ISTVS*, 2: 699-735. Hanover, N.H.: ISTVS.
450
- 451 Maclaurin, E. B. (1984). A rig for testing the soft soil performance of track systems. In
452 *Proceedings 8th International Conference ISTVS* 1: 291-311. Hanover, N.H.: ISTVS.
453
- 454 Mardani, A, Shahidi, K. and Karim-Maslak, H. (2010). An Indoor Traction Measurement
455 Systems to Facilitate research on Agricultural Tires, *Journal of Food, Agriculture and*
456 *Environment*, Vol 8
- 457 Manuwa, S. I. (2002). Development of Equipment for Soil Tillage Dynamics and Evaluation of
458 Tillage Parameters, PhD Thesis, Federal University of Technology, Akure, Nigeria,
459 347 pp.
460
- 461 Manuwa, S. I. and Ademosun, O. C. (2007). Draught and Soil Disturbance of Model Tillage
462 Tines under Varying Soil Parameters. *Agricultural Engineering International, the CIGR*
463 *Ejournal (U S A.).* Vol. IX, March 2007, pp 1-18.
464
- 465 Manuwa, S. I. (2009). Performance evaluation of tillage tines operating under different depths
466 in a sandy clay loam soil. *Soil and tillage research*, 103: 399- 405.
467
- 468 Manuwa S. I. and Ajisafe A.A. (2010). Development of Overhead Gantry as Complementary
469 Equipment to Indoor Soil Bin Facility. *Journal of Food technology* 8(3): 92-95.
470

- 471 Manuwa, S.I., O.C. Ademosun, A. S., L.A.S.Agbetoye; A. Adesina. (2011). Development of
472 Outdoor soil bin facility for soil tillage dynamics research. *Journal of Agricultural*
473 *Engineering and Technology (JAET)*, Vol. 19 (1): 1-8. Nigeria.
- 474
- 475 Plackett, C. W. (1985). A review of force prediction methods for off-road wheels. *Journal of*
476 *Agricultural Engineering Resource* 31: 1-29
- 477
- 478 Patel, N. M., and Godwin, R. J. (2008). Controlled Soil Bin Tests for Pneumatic Tyres at Heavy
479 Loads. An ASABE Meeting Presentation. Paper Number:083543 for 2008 ASABE
480 Annual International Meeting, Providence, Rhode Island, 28 June – 3 July 2008.
- 481 Pandey K.P., Tiwari G.S. (2006). *Rolling Resistance of Automobile Discarded Tyres for Use in*
482 *Camel Carts in Sand*. Presented at 2006 Annual international meeting of ASABE,
483 Oregon Conventional center Portland, Oregon, 2006.
- 484
- 485 Persson, S. (2009). Basic Traction Mechanics. *Advances in Soil Dynamics, Vol. 3*. ed. S.K.
486 Upadhyaya, W.J. Chancellor, J.V. Perumpral, D. Wulfsohn, and T.R. Way, Ch. 2, 25 -
487 58. St. Joseph, Mich.: ASABE
- 488
- 489 Reece, A.R., (1964). Problems of soil-vehicle mechanics. Land Locomotion Laboratory Report
490 No. 8470 (LL97). Warren, Mich.: U.S. Army Tank Automotive Center.
- 491
- 492 Rohlf, R. A., L. G. Wells, and Z. X. Xing. (1994). Analysis of wheel compaction using a soil
493 stress-strain finite element model. ASAE Paper No. 94-1546. St. Joseph, Mich.: ASAE
- 494
- 495 Ronai, D., I. Schmulevich, and D. Wolf. (1994a). A new field single wheel tester. In *Extended*
496 *Abstracts of the 2nd International Conference on Soil Dynamics*, 80-81. Silsoe, Bedford,
497 UK: Silsoe College.
- 498

- 499 Ronai, D., I. Schmulevich, and D. Wolf. (1994b). A new field single wheel tester. (This paper is
500 supplemental to *Extended Abstracts of the 2nd International Conference on Soil*
501 *Dynamics*, 80-81.) Silsoe, Bedford, UK: Silsoe College
- 502
- 503 Taghavifar H. and A. Mardani.(2012). Contact Area Determination of Agricultural Tractor
504 Wheel with Soil. *Cercetari Agronomice in Moldova* Vol. XLV, No. 2 (150): 15 – 20.
- 505
- 506 Taghavifar, H.and Mardani, A. (2014). Analyses of energy dissipation of run-off-road wheeled
507 vehicles utilizing controlled soil bin facility environment. *Energy* 66 (2014) 973 - 980
- 508
- 509 Taghavifar, H.and Mardani, A. (2015). Net Traction of a Driven Wheel as Affected by
510 Slippage, Velocity and Wheel Load. *Journal of Saudi Society of Agricultural Sciences*
511 14, 167 – 171
- 512
- 513 Upadhyaya S. K., Mehlschau, J, Wulfsohn, D, and J. L. Glancey (1986). Development of a
514 Unique, Mobile, Single Wheel Traction Testing Mchine. *American Society of*
515 *Agricultural Engineers*, Vol. 25 (9): 1243 – 1246.
- 516 Upadhyaya, S. K., and D. Wulfsohn. 1993. Traction prediction using soil parameters obtained
517 with an instrumented analog device. *J. Terramechanics* 30(2): 85-100.
- 518
- 519 Upadhyaya, S. K., and American Society of Agricultural Engineers. (1994). *Advances in soil*
520 *dynamics*. American Society of Agricultural Engineers.
- 521
- 522 Upadhyaya S. (2009). Traction Prediction Equations. *Advances in Soil Dynamics, Vol. 3.* ed.
523 S.K. Upadhyaya, W.J. Chancellor, J.V. Perumpral, D. Wulfsohn, and T.R. Way, Ch. 2,
524 161 - 186. St. Joseph, Mich.: ASABE
- 525 Way, T. R. (2007). Three single wheel machines for traction research. ASABE Paper No. 07-
526 1109. St. Joseph, Mich.: ASABE.
- 527

- 528 Wood, R. K., and L. G. Wells. (1983). A soil bin to study compaction. ASAE Paper No. 83-
529 1044. St. Joseph, Mich.: ASAE.
530
- 531 Wells, L. G., and J. D. Buckles. (1987). PC-controlled soil/tire tester. ASAE Paper No. 87-1014.
532 St. Joseph, Mich.: ASAE
533
- 534 Wells, L. G., J. Yaping, and Z. X. Xing. (1996). Measuring three-dimensional soil deformation.
535 *Journal of Terramechanics* 33(6): 281-292
536
- 537 Wismer, R.D. and H.J. Luth. (1973). Off-road traction prediction for wheeled vehicles. Journal
538 of Terramechanics, 10(2):49-61.
539
- 540 Wong J. Y. (1984). On the Study of wheel-soil Interaction. Journal of Terramechanics 21 (2):
541 117 - 131
542
- 543 Wong, J. Y. (1989). *Terramechanics and Off-Road Vehicles*. Elsevier.
544
- 545 Wu, Y.-C. (2000). Handling of multi-axle, all-wheel-drive off-road vehicles. PhD. diss. Ottawa:
546 Carleton Univ., Dept. of Mechanical and Aerospace Engineering.
547
- 548 Wulfsohn, D. (2009). Traction device-soil interfacial behavior. In *Advances in Soil*
549 *Dynamics*. Vol. 3. S. K. Upadhyaya, W. J. Chancellor, J. V. Perumpral, W. R. Gill, T. R.
550 Way, and D. Wulfsohn, eds. St. Joseph, Mich.: ASABE.
551
- 552 Yahya, A., Zohadie, M., Ahmad, D., Elwaleed, A. K., and Kheiralla, A. F. (2007). UPM indoor
553 tyre traction testing facility. *Journal of Terramechanics*, Vol 44(2): 293–301.
554 <http://doi.org/10.1016/j.jterra.2007.03.002>
- 555 Yong, R. N., E. A. Fattah, and N. Skiadas. (1984). *Vehicle Traction Mechanics*. Elsevier
556 Amsterdam
557 .

- 558 Zoz, F. M., and R. D. Grisso. 2003. Traction and tractor performance. ASAE Distinguished
559 Lecture Series. Tractor Design No. 27. St. Joseph, Mich.: ASAE.

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