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 ~~future~~ 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 continue

35 to be on the increase. This demand will call for higher level of agricultural mechanization and

36 corresponding increase in size of agricultural machinery. Increasing weight of agricultural machinery is

37 not without its negative side effects which is soil compaction. Soil compaction retards crop germination,

38 growth and yield. It decreases water infiltration into the soil and increases surface water runoff and

39 erosion. This type of soil degradation is also common with the use of forestry machinery and off- the road

40 military equipment. In order to make the soil serve man sustainably, the study of soil dynamics in traction

41 is *sine qua non*.

42 Terrain may be defined as a stretch of land, especially with regard to its physical and/or natural features.

43 Traction can also be defined as the ability of vehicle's tractive element to generate enough forces/thrust to

44 overcome all types of vehicle resisting forces and hence keep the vehicle in constant travel (Yong *et al.,*

45 *1984*). The study of interaction of terrain with machine usually called soil-machine interaction can be

46 classified into two (Ani et al., 2014): interaction of the soil and the tractive element e.g. wheel or track;

47 interaction of the soil with tools e.g. tillage tools, planters, fertilizer applicators, harvesting tools and other

48 soil-engaging tools. The first is known as traction studies while the second is called tillage studies.   In

49 traction studies, interaction between vehicle and terrain is achieved through the running gear system,

50 which produces reaction and responses at the terrain interface. The greater the ability of the terrain

51 material and the interactions at the interface to transfer the thrust action into the substrate, the better the

52 capacity of the vehicle to achieve maximum tractive efficiency (Yong et al. 1984).

53 For optimum mobility to occur, it is required that the vehicle be able to move from one point to another

54 with minimum amount of motion loss and energy input. To achieve this, the terrain must provide

55 floatation as well as resistance capability such that enough thrust can be developed between the running

56 gear contact element and terrain material itself with minimal wheel slippage.

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

2. Developments in Traction Soil Bins and Single Wheel Testers

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

81   m. The system was designed to provide an infinitely variable vertical load up to a maximum of

82   26.7 kN and a draft load up to a maximum of 13.3 kN.

83   Patel and Godwin (2008) carried out a study on controlled soil bin tests for pneumatic tires). In

84   the study, a single wheel test bed (Figure 1) was developed for performing wheel-soil interaction

85   study at heavy wheel loads under controlled environment. The tests were performed on soft and

86   hard surfaces characterized by soil and concrete respectively on the soil bin.

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

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

89   tropical soils was designed and developed. The developed facilities consists of a moving carriage with a

90   cantilever-mounted tire that moves in either forward or reverse directions on wall rails above a soil tank.

91   The facility set-up was able to operate in either: (a) towing test mode for tire motion resistance studies or

92   (b) driving test mode for tire net traction and tractive efficiency studies. The test tire on the moving

93   carriage under the towing test mode was to operate and engage onto the soil surface in the tank through a

94   chain drive system. Under the driving test mode, the test tire on the moving carriage was powered to

95   rotate by a motor and a gearbox system with an additional pull provided by a cable-pulley mechanism

96   connected to a tower with hanging dead weights. The long soil bin however results in testing high lug

97   agricultural tires at towed and driving modes for their motion resistance, net traction and tractive

98   efficiency at different soil conditions. The facility can also be used for testing the effects of other

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

100   performances of the tire.

101

102   Taghavifar and Mardani (2012) carried a study on contact area determination of Agricultural tractor

103   wheel with soil. In the study, an experimental test was conducted inside a soil bin facility providing

104   entirely reliable and controlled condition for the test. The test had the advantage of utilizing images taken

105   of the contact areas and subsequently, using a planimeter to obtain the values of contact area precisely.

106 Test variables that were the two most prominent and influential parameters were tire inflation pressure

107 and vertical load applied on wheel. Similarly, Taghavifar and Mardani (2014) carried out a study on

108 evaluation and measurement of the performance parameters of agricultural wheels. In the study, a single-

109 wheel tester (Figure 3) was designed, constructed and evaluated inside a soil bin. The tested wheel was

110 directly driven by the electric motor. Vertical load was applied by a power bolt on wheel. This tester

111 could measure required draft force, the depth of tire sinkage, contact area between wheel and soil, and soil

112 stress at different depths both alongside and perpendicular to the direction of traversing. In order to

113 evaluate the system performance, traction force was measured by the connected S-shaped load cell at

114 arms between the wheel-tester and carriage.

115 Ahmad et al. (2011) reported a motion resistance rig (Figure 4) that was designed to measure the

116 towing force of a single test wheel towed by a tractor. Taghavifar and Mardani (2015) reported on

117 single wheel tester (Figures 5 and 6) at the Department of Agricultural Machinery of Urmia

118 University, Iran to study the effects of slippage, velocity and wheel load on net traction. Some

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

120 3. **Motion Resistance and Measurement**

121 According to Ahmad et al.(2011)), motion resistance can be regarded as the total drag opposite to the

122 steady motion of a free motion wheel across a horizontal surface. To them, it can also be defined as

123 integral of the horizontal component of the radial stresses. Motion resistance refers to the resistance to

124 motion of a wheel caused by the absorption of energy in the contacting surfaces of the wheel and the soil

125 upon which the wheel rolls. The motion resistance may be expressed as reported by Ahmad et al. (2011)

126 in Eq. (1).

127 $MR = MR_c + MR_b + MR_t$ (1)

128 The total motion resistance force, MR is made up of the MR_c, the component due to soil compaction,

129 MR_b, the component due to horizontal soil displacement and MR_t, the component due to flexing of the

130 tire. For vehicle operating on a hard surface, MR_t, constitutes the largest percentage of the motion

131 resistance force and this, can be slightly reduced by increasing the inflation pressure and the effective

132 stiffness of the tire. In off-road situations, however, the components MR_c and MR_b make up the largest

133 proportion of the motion resistance force and increasing the inflation pressure and the tire stiffness have

134 shown to increase the motion resistance Plackett (1985).

135 Usually, the motion resistance is expressed in terms of motion resistance ratio (τ). Mathematically, the

136 motion resistance ratio is as expressed as shown in Eq. (2).

137 $MMR(\tau) = \frac{MR}{W}$ (2)

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

139 The performance characteristics of a towed wheel are described usually by a towing force (motion

140 resistance), sinkage and skid. The most pertinent parameter of the towed pneumatic wheel is the motion

141 resistance, which is influenced by the tire design, system parameters and terrain characteristics.   In

142 studying the soil-wheel interaction, the behavior of the soil and the most important design parameters of

143 the wheel form the basic inputs (Pandey and Tiwari 2006).

144 Traditionally, design parameters of the tire include diameter of the wheel, section width, section height,

145 inflation pressure and load deflection relationship. All these are considered to have varying degree of

146 influence on the tire soil interaction. The terrain characteristics include the types of soil, soil moisture

147 content and its compaction level and the system parameters comprise the dynamic (normal) load on the

148 wheel and forward speed. The dynamometer reading is usually always taken to determine the towing

149 force.

150

151

152 **4. Traction**

153

154 Traction may be defined as the force derived from the interaction between a device and a

155 medium that can be used to facilitate a desired motion over the medium (Gill and VanDen Berg,

156   1968). Net traction, can be defined (ASAE S296.5 2009) as the force parallel to the direction of

157   travel, developed by the traction device and transferred to the vehicle. Gross Traction is the sum

158   of net traction and motion resistance.

159   Tractive effort developed by off-road vehicles has been of interest to people engaged in

160   agricultural, forestry, military and mining operations. Most research conducted in off-road

161   traction mechanics has focused on either agricultural or military equipment (Persson, 2009)

162   Tractive performance is affected by both the soils' normal strength and its shear strength. In general,

163   normal strength has the most effect on motion resistance, while shear strength has the most effect on

164   travel reduction. Describing and documenting the soil is perhaps the most difficult part of traction testing.

165   There are several reasons for the difficulty. First, the soil has sufficient variation, which can easily

166   influence the soil sampling device. Second, soil measurements are time consuming, and finally, the

167   sampling technique may not be replicated or repeated for different soil conditions. For this reason, much

168   of the traction tests reported are of a comparative nature, that is, one traction device compared to another

169   device while operated under the same soil conditions. The device that is the most portable and commonly

170   used, the cone penetrometer, works well only if the soil has moisture and if it has not been disturbed. Soil

171   strength as measured by the soil cone penetrometer provides a combined measurement of soil normal

172   strength and shear strength. The cone penetrometer also requires a large number of measurements because

173   there is a large variability in the test results.

4.1 Traction Parameters

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

176   performance:

177   • Travel reduction ratio (TRR), commonly called "slip" and expressed in percent.

178   • Net traction ratio (NTR), sometimes called pull/weight ratio.

179   • Tractive efficiency (TE) usually thought of as percent but used as a ratio in this paper.

180   • Gross traction ratio (GTR).

181   • Motion resistance ratio (MRR).

182   The traction parameters involving forces are all normalized by dividing by W_d, the dynamic force reaction

183   supporting the wheel or traction device. W_d includes static axle weight and any weight transfer that might

184   take place during the testing process, that is, the total reaction force. Dividing by W_d allows comparisons

185   between tires and other tractive devices of different sizes and weights, and provides a dimensionless

186   parameter for traction comparisons. It is important to note that the above parameters apply to a traction

187   device and not necessarily to a vehicle (Zoz and Grisso, 2003).

188

189 5. **Measurement and Data Acquisition**

190   Data acquisition and control computers and all the associated recording and display equipment are

191   required to process data acquired during the conduct of test programs. In addition to coordinating data

192   acquisition, the package may also provide computer control of the test units.

193   For effective work and utilization of soil bin in traction studies, commercially available measuring and

194   recording equipment should be used where necessary. It is expected that as measurable parameters are

195   identified, new measuring devices should be developed so that their importance in soil machine - relations

196   can be determined by physical measurements. Direct access to instrument manufacturers, who share in

197   the development of new measuring devices, provides an effective way of securing best designs. An

198   overall goal of soil dynamics will permit manipulation of soil from an initial known condition into a new

199   and specified condition; digging, cutting, loading and transport of soil in effective and efficient ways;

200   attainment of adequate tractive forces in effective and efficient manners; mobility across terrain with a

201   variety of conditions; and prediction of soil behavior under the action of dynamic loads applied by

202   machines and vehicles (Upadhyaya, S. K 1994).

203   The Data acquisition system for the test facility is usuall located on a special place on the carriage close

204   to the soil bin facility. This dedicated system is made up of some sensor outputs interfaced to a computer

205   system. The computer system can receive, monitor, display and store the measured signals from the

206 respective transducers. AC program is used to retrieve and read the stored data and compute average,

207 standard deviation and variance of the needed tire performance measurements. An optic tachometer that

208 is located on the main drive shaft of the carriage driving unit measures the moving carriage speed. This

209 unit can detect revolutions in digital values without making direct contact. In detecting revolutions, the

210 optic tachometer senses the special color sign that is located on the revolving shaft and detects signals

211 equals to the numbers of the revolution of the rotating main drive shaft. A notebook may be used for

212 data acquisition system, monitoring and real time control of the system. In any mode, data acqusiition

213 system may perform at different sampling rates. The display of data is available to user at real time on

214 the computer monitor screen and the data could be permanently stored in a defined file in the computer

215 (Mardan *et al* 2010).

216 6. **Traction Prediction Equations**

217 According to Upadhyaya (2009) numerous attempts have been made to quantify soil-traction device

218 interaction. These attempts can be classified under the following three broad categories: (1) analytical

219 methods; (2) semi-empirical, parametric or analog methods; and (3) empirical methods.

220 **6.1** The **analytical or theoretical approach** assures a certain level of understanding of the basic process

221 (Freitag, 1985). In order to predict the performance of a traction device, we need to know the distribution

222 of normal and shear stress at the soil-tire/track interface and the geometry of the 3-D contact surface.

223 Wulfsohn (2009) has provided an extensive review of soil-wheel interaction surface geometry and

224 distribution of stresses at the soil-traction device interface.

225 **6.2** The **semi-empirical or parametric approach** utilizes two analog devices to represent soil-traction

226 device interaction. Vertical deformation of the soil under load is assumed analogous to soil deformation

227 under a flat plate. The shear deformation of the soil under a traction device is assumed to be similar to

228 the shear due to a torsional shear device or a rectangular grouser unit. The normal stress under a flat

229 plate is assumed to be of the form (Bekker, 1960 and Wong, 1984):

230
$$P = \left(\frac{K_c}{b} + K_\varphi \right) z^n \qquad (3)$$

231   where p is normal pressure under the plate, b is minimum dimension of a rectangular plate; the diameter

232   for a circular plate, z is soil deformation and K_c , K_φ and nare soil parameters

233   Although several different expressions are available to relate shear stress to soil deformation (Bekker,

234   1960, 1969; Yong et al., 1984), the Janosi and Hanamoto (1961a, b) relationship is most widely used in

235   agriculture:

236
$$\tau = \tau_{max} \left(1 - e^{-j/k} \right) \qquad (4)$$

237   where τ is shear stress,

238     $\tau_{max} = c + p \tan \varphi = $ max shear stress,

239     $$\tau_{max} = c + \sigma \tan \varphi = \max \ shearstress$$

240   c is cohesion, σ is normal stress, φ is soil internal friction angle, j is shear deformation and k is shear

241   modulus.

242   It was reported (Upadhyaya, 2009) that:

243
$$Z_0 = \left[\frac{P_{gr}}{K_c/b + K_\phi} \right]^{1/n}$$

244
$$MR = \left[\frac{b p_{gr}^{(n+1)/n}}{(n+1)\left[\frac{K_c}{b} + K_\varphi \right]^{1/n}} \right] \qquad (5)$$

245   Where Z_0 is maximum deformation, p_{gr} is average ground pressure equal to $p_c + p_i$, p_c is pressure due to

246   carcass stiffness, p_i is tire inflation pressure and MR is motion resistance.

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

248 $$P = \left(cK'c + \gamma bK'_\varphi\right)\left(\frac{Z}{b}\right)^n \qquad (6)$$

249 where K'c, K'φ, n = dimensionless constants and γ = weight density of soil. Upadhyaya et al. (1993)

250 found that predictions based on this equation were more consistent with their field data than were

251 predictions made using Eq. (3).

252 According to Goering et al. (2006), this approach has been useful for explaining some aspects of tractive

253 device-soil interaction; however, semi-empirical approach has limited practical application.

254 **6.3 Empirical Approach.** This approach evolved at the end of World War II as a means of measuring

255 trafficability of soil at the U.S. Army Corps of Engineers Waterways Experiment Station (WES). It was

256 intended for quick numerical evaluation of soil in the field (Upadhyaya, 2009). It is based on soil cone

257 index as the only soil strength parameter. On the basis of numerous tests conducted at WES, primarily

258 on fine-grained wet clay soil and coarse-grained dry Yuma sand, vehicle cone index (VCI) was

259 developed to determine a "go-no go" criterion for military vehicles (Freitag, 1985; Wong, 1989). The

260 VCI was based on measured soil cone index values. Goering *et. al*. (2006) reported that empirical

261 methods using field and/or soil bin laboratory tests of traction devices either by themselves or as part of

262 a complete vehicle are the most used technic for assessing tractive performance by both vehicle and

263 traction device manufacturers.

264 Several empirical equations for traction prediction have been developed by researchers. Wismer and Luth

265 (1973) developed a traction prediction equation for a single powered wheel. The equation is an

266 exponential function of travel reduction and is rewritten (Eq. 7) as:

267 $$NTR = \frac{P}{W} = 0.75\left(1 - e^{(-0.3C_n S)}\right) - \left(\frac{1.2}{C_n} + 0.04\right) \qquad (7)$$

268 Where NTR is net traction ration, P is net wheel pull, W is dynamic wheel load, C_n is wheel numeric,

269 $(C_n = CIdb/W)$, CI is soil cone index, d is unloaded tire diameter, b is unloaded tire width and S is travel

270 reduction (fraction). Wheel numeric is a simplified wheel-soil contact model based on dimensionless

271 parameters. Wismer and Luth also derived an equation for predicting the motion resistance ratio, which is

272 the last expression of (Eq.7):

273
$$MRR = \frac{1.2}{C_n} + 0.04 \qquad (8)$$

274 Where MRR is the motion resistance ratio, which is the ratio of the wheel motion resistance to the

275 dynamic wheel load. The traction equation given by Gee-Clough et al. (1978) takes a similar form as that

276 developed by Wismer and Luth (1973) to model mobility number, M. The equation is of the form (Eq. 9):

277

278
$$M = \frac{CIdb}{W} \left(\frac{\delta}{h}\right)^{0.5} \left[\frac{1}{1 + \frac{b}{2d}}\right] \qquad (9)$$

279

280 where M is mobility number, δ is tire deflection and h is tire section height. The mobility includes wheel

281 numeric used by Wismer and Luth. Mobility number is used to predict the combined effect of soil-wheel

282 parameters on the tractive performance.

283 Brixius (1987) presented traction prediction equations for single bias ply tires. His equations were

284 revisions of equations developed by Wismer and Luth (1973). The equations are rewritten as:

285
$$\frac{GT}{W} = 0.88\left(1 - e^{(-0.1B_n)}\right)\left(1 - e^{(-7.5S)}\right) + 0.04 \qquad (10)$$

286
$$MRR = \frac{1}{B_n} + 0.04 + \frac{0.5S}{B_n^{0.5}} \qquad (11)$$

287 Where GT is gross traction and B_n is called mobility number defined by Brixius as (Eq. 12):
288

289 $$B_n = \frac{CIdb(1 + 5\delta/h)}{W(1 + 3b/d)}$$ (12)

290
291 These and several other researchers have reported several models for wheel numeric, motion resistance
292 ratio and mobility number.

293
294
295 **7.Development of Soil bin at FUTA and Future work**

296
297 Some efforts have been made to conduct research in soil dynamics in tillage at the department of

298 Agricultural and Environmental Engineering of FUTA. The department has developed both indoor and

299 outdoor soil bins (Figs. 7 – 9) and various studies have been reported (Manuwa, 2002; Manuwa and

300 aAdemosun, 2007; Manuwa, 2009; Manuwa and Ajisafe, 2010; Manuwa et. al., 2011; Ajewole and

301 Manuwa, 2014a, b). Further work is in progress in soil dynamics in tillage and traction. Single wheel

302 tester is being developed for another indoor soil bin in the Soil dynamics laboratory. Terrain

303 characterization is also an area of study we need to research into.

304 **8. Conclusions**.

305 Soil dynamics in traction has been reviewed with the aim of enlightening, motivating and challenging

306 would-be researchers in the specialized field. It is noted that although a lot of research has been done by

307 researchers in developed countries, however there is a dearth of publication from Nigerian researchers.

308 Some efforts have been made by researchers at FUTA to study soil dynamics in tillage and more efforts

309 are required to intensify studies in traction which they have embarked upon.

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489 **Figure1.**Off road dynamic facility – soil bin
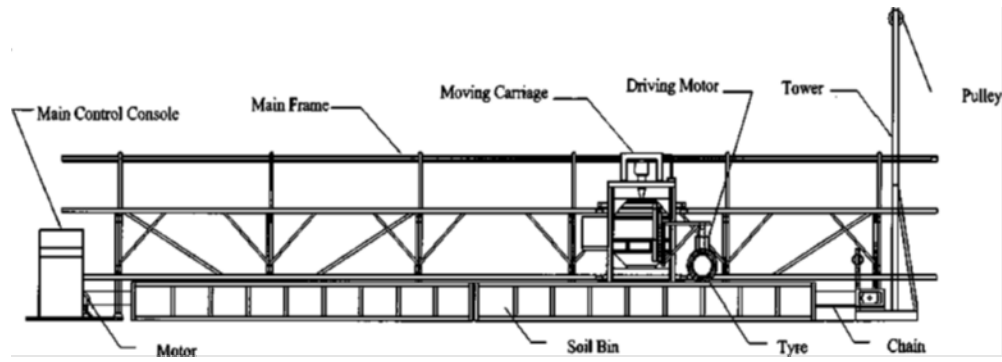490 Source: (Patel and Godwin, 2008)

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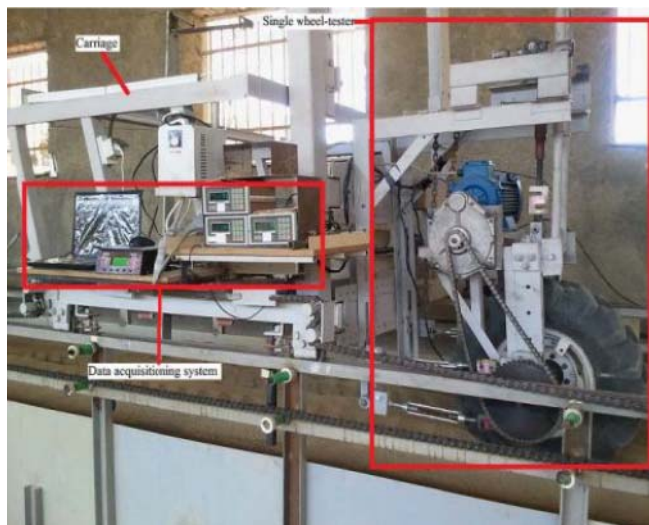**Figure 2**   Schematic diagram of a long soil bin for tire traction testing facility
Source: (Yahya *et al.,* 2007)

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Figure3 The General Overview of the Testing Facility
Source: Taghavifar and Mardani (2014)

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515   1.   Test wheel   2. Load hanger   3. Load   4. The BFG   5. Three point hitch frame
516   6.   Connecting cable   7. Notebook PC

517 **Fig**ure 4.Test rig coupled to the tractor during field test
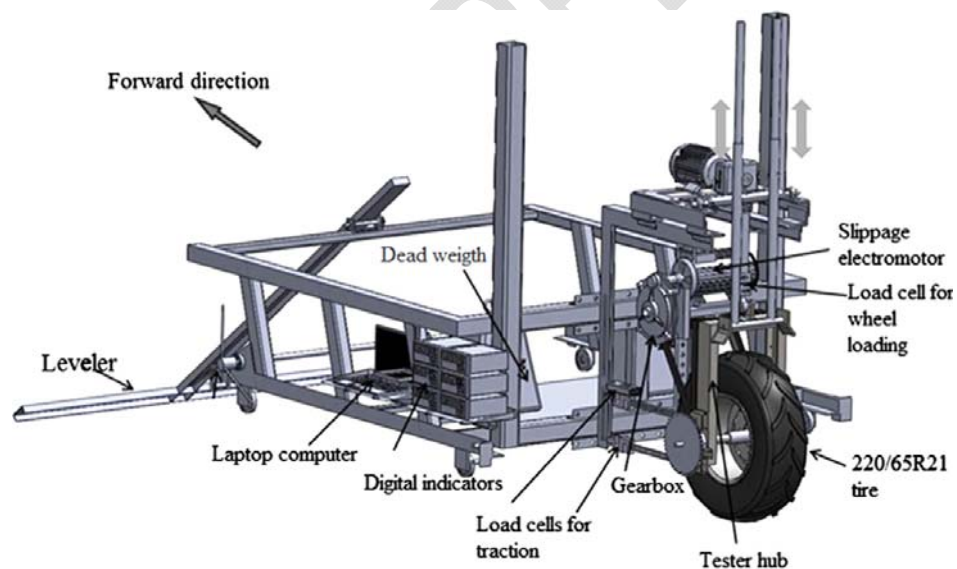518   Source: (Ahmad *et al.,* 2011)

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

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Figure6. Schematic of the utilized single-wheel tester along with its detailed components
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533   Source: (Taghavifar and Mardani, 2015).

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

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

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

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568 **Table 1:**Some Single wheel Tester used in Soil bins and in the field (a) In Soil bins

569 (b) In the field

Institution	Range of wheel diameter (mm)	Max dynamic load, kN	References
USDA-ARS-NSDL (Auburn, Alabama	1265 - 1880	44	Burt et. al.1980; Lyne et al.1983; Way, 2007
University of Kentucky, Lexington, Ky	- 745 max.	9.8	Wood and Wells, 1983; Wells and Buckles, 1987; Rohlf et al., 1994; Wells et al., 1996.
Carleton University, Ottawa, Ontario, Canada	- 1200	11.2	Wu, 2000
Technical University of Munich, Munich, Germany	500 -1200	Using Dead weights	Krick, 1973
Cranfield University at Silsoe, Silsoe Bedfordshire, U. K	500 - 1400	123 Through hydraulic cylinders	Godwin et. al., 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 et al.,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 et al., 1994 a, b

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