Evaluation of five traction models for agricultural tractors in Colombia

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Abstract: The behavior of traction devices of agricultural tractors has been modeled by analytical techniques and through the use of empirical equations, the latter methodology has shown good results and numerous applications. This article presented the evaluation of four empirical traction models and one semi-empirical in order to establish the model that best fit to Colombian agricultural soil mechanization and to propose a tool that better assess the traction behavior of tractors in the field. Taking into account all terrains conditions evaluated, the model that best adjusted was the Gee-Clough and collaborators model and it was possible to explain the 90% of the draft forces measured. Also the model of Evans and others, using improved prediction coefficients of Deere Group Research model, which fit in soils with vegetable cover, got a coefficient of determination of 94% in draft forces estimation under these conditions. All comparable observations were made with tractors in 2WD (two wheel drive) mode, it was suggested that tests with tractors in 4WD (four wheel drive) mode should be run.

Keywords: traction, empirical models, tractors, soils, mechanization.

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1 Introduction

The most common application of high energy requirement of the agricultural tractor is soil preparation with implements hitched to the drawbar ，and sometimes in the three point hitch. In both situations, the draft force required to perform the specific agricultural labor is available due to the balance of forces at the interface agricultural soil-tractor or better soil- traction device (in most cases, the traction device is a tire), through the phenomenon called TRACTION.

The interaction of traction device (tire) - soil is a very complex phenomenon that involves stresses and strains in the one and the other. According to Yong et al. (1984)，the formal approach to the study of traction had included: i.) Mathematical models based on the limit equilibrium machine interaction–soil where it is assumed that the soil is completely rigid to the point of failure, then it flows steady under constant stress, resulting in a differential equation for limit equilibrium under conditions of plane strains for a soil that obeys the criterion of Mohr-Coulomb failure; ii.) Applying the principles of conservation of energy to mechanical traction, generating an energy model with its resulting differential equations; and iii.) Finite element models applied to the analysis of the mobility of vehicles, establishing continuum mechanics models in general and interaction tool-soil in particular, through the use of stress-strain relationships, where the soil failure may or may not occur under the traction load.

The above formal methods have not come to common practice in field use of agricultural tractors , as have been verified by Gee- Clough (1980), Volfson (1984), Wong (1984), Al -Hamed et al. (1994), and GrissoZoz (2003), Lyasko (2010), Tiwari et al. (2010) and Keen et al. (2013).

The traction behavior has been simulated and estimated by empirical correlation techniques over the past four decades and even today many of the models used to

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estimate the characteristics of traction in agricultural tasks, for design and selection of tires and all practical use recommendations in tractor field operation are based on empirical equations of estimation, as are verified in agricultural conditions of various countries, Iff et al. (1984) Colvin et al. (1989), Grisso et al. (1992), Clark et al (1993), Jenane and Bashford (2000), Al-Hamed and Al-Janobi (2001), Saarilahti (2002), Zoz and Grisso (2003), Catalan et al. (2008), Sahu and Raheman (2008), Pranav and Pandey (2008) Kumar and Pandey (2009), Servadio (2010), Lyasko (2010) Kolator and Bialobrzewski (2011) and dos Santos Machado (2011). Perhaps, there exists a semi-empirical approach developed by Bekker, which allows a prediction of some variables with the traction equations involving the estimation of the stress state at the interface soil-wheel, Bekker (1960), Wong (1984), Yong et al (1984), Lyasko (2010) and Keen et al. (2013).

Zoz and Grisso (2003) mentioned that these traction equations provide a basis for estimating the operation of tractors in the field when combined with basic information from official testing tractors, others authors: Gee-Clough (1980), Iff et al. (1984) Colvin et al. (1989), Grisso et al. (1992), Clark et al. (1993), Al-Hamed et al. (1994), Schlosser et al. (2001), Al-Hamed and Al-Janobi (2001), Zoz and Grisso (2003), Catalan et al. (2008), Sahu and Raheman (2008), Pranav and Pandey (2008) and Kumar and Pandey (2009), agree and state that such models can be incorporated into appropriate algorithms that are programmed and should enable researchers and designers to research many problems related to the tractor operation under widely varying conditions in order to make more reliable designs in tractors, optimize operational parameters and improve tractor-implement balance, without extensive and costly research program in the field.

The aim of this study is to conduct a comparison between four empirical models and one semi–empirical model of traction for estimating traction parameters measured and calculated at the field tests, in order to establish the model that best accommodated to native conditions and propose a tool that enables the best estimate of the behavior of traction devices and hence agricultural tractors in the country.

2 Materials and methods

A set of 86 individual runs or observations was formed. The original data come from one publication of the Annual Reports of the Agricultural Machinery Program of the Colombian Agricultural Institute (ICA) from 1983 to 1991 and two internal documents of evaluation machinery of that program, namely: “Comparative evaluation of the traction effect of two agricultural pneumatic wheels” ICA Journal, 18 (4), 1983, pp . 363-373; “Evaluation of the Lister Pico tractor” (Internal Document, 1987) and “Evaluation of agricultural tires in poor traction conditions” (Internal Document, 1991).

For each test, four data sets were selected: The traction device (agricultural tires); the used vehicle (tractor); the support terrain (agricultural soil) and the system.

2.1 General characteristics of the data set

• Tires (all have diagonal plies):

Undriven steered wheels (front tires): 6.50-16 to 11-16, the section width for these tires ranged from 188 to 338 mm; the overall diameter from 759 to 965 mm. It was assumed for all tires a deflection/section height ratio equal to 0.2 as outlined in Gee-Clough (1980) in consideration of regular loads and inflation pressures, static radius between 353 and 434 mm and 406 mm rim diameter.

Front drive tires (with lugs): 9.5-24 to 12.4-28, Section width between 262 and 340 mm; overall diameter from 1046 to 1255 mm; ratio deflection / section height = 0.2; Static radius between 483 and 577 mm and rim diameter between 610 and 711 mm.

Rear tires (drive wheels):11.2-24 to 23.1-30, Section width 305-630 mm, overall diameter between 1102 and 1715 mm; deflection ratio/height section between 0.088 and 0.102 when measured in poor traction conditions and

0.2 when it was estimated; static radius between 498 and 777 mm and rim diameter between 610 and 762 mm.

• Tractors:

PTO (Power take off) rated power: 19.4 to 90.2 kW

Rear static weight: 12.6 to 49.4 kN (in 66 runs were measured)

Front static weight: 7.9 to 17.2 kN (in 66 runs were measured)

Wheelbase: 2.11 to 2.71 m (in 66 runs were measured)

Height of drawbar: 0.274 to 0.530 m (in 66 runs were measured)

Feed speed: 0.81 to 2.31 m/s (2.90 to 8.33 km/h)

•Terrain (soil):

Cone index (CI): 102-1200 kPa (17 were measured, estimated 69)

The estimates were made according to soil texture, its moisture content and surface condition and as recommended by Gee- Clough (1980), Dwyer (1984), Brixius (1987) and Whitney (1988).

The following strength values are in regard with the theory of plates used in the semi-empirical method of Bekker and were estimated according to the characteristics of the test soils and according to the recommendations of Bekker (1969) cited by McKyes (1989) , Soltynski cited by Bernacki et al (1972) , Dwyer et al. (1974) , Inns and Kilgour (1978) , Volfson (1984) , Shibusawa and Sasao (1996) , Upadhyaya et al. (1997), Okello et al. (1998) , Shmulevich and Osetinski (2003) and Wong and Huang (2006)

Cohesion (c): 5-50 kPa

Internal friction angle (Φ): 13-36 °

Cohesive modulus of soil deformation (k_c): 4-30 kPa/m^{n-1}

Friction modulus of soil deformation (k_Φ): 153-1800 kPa/m^n

Exponent of soil deformation (n): 0.12 to 0.8

Soil deformation modulus (K): 6 - 13 mm

• System:

The measured draft forces ranged from 0.8 to 28.3 kN

The measured slips ranged between 1.6 % and 51.4 %.

All tests were made by loading the tractor with implements hitched to the drawbar and maintaining the draft force approximately horizontal to remove any component of weight transfer from implements. The necessary calculus of the dynamic weight transfer coefficient is then made with the simple Zoz ́s (1972) methodology and as it was used by Lee and Kim (1997).

2.2 Description of testing methodology

It was defined the condition of zero slippage as zero force on the drawbar on the test surface (before being altered by the action of the implement used as a load). A more complete discussion about it can be found in Shibusawa and Sasao (1996), Sharma and Pandey (1998) and Schreiber and Kutzbach (2007).

The draft force was determined by interlacing a hydraulic dynamometer between the drawbars of tractor and implement. This device was previously calibrated in the laboratory to establish the relationship between the draft force and pressure.

In each terrain it was made a qualitative observation of the surface condition of field test, in terms of the presence or absence of vegetation cover, grass surface, ratoon, etc., consistency of the soil and the surface roughness (plowed, secondary tilled, etc.), description of the soil condition required for behavior evaluation of traction in each case. In 17 cases, it was measured the cone index soil with a manual electronic recording penetrometer with cone angle 30 ° and cone base diameter 20.27 mm, the values of penetration resistance correspond to the range of depth of 0-15 cm under the soil conditions and the type of tire.

2.3 Data processing

Four empirical models and one semi-empirical model were selected:

MODEL 1: Wismer and Luth

MODEL 2: Brixius

MODEL 3: Evans, Clark and Manor

MODEL 4: Gee- Clough, McAllister, Pearson and Evernden

MODEL 5: Bekker (semi-empirical)

For each of these models, a spreadsheet file (not presented) was written with the basic information mentioned at the beginning of this article and adding the necessary calculations to establish traction parameters according to equations using in each of the models. They were calculated: draft force in the tractor drawbar and slippage of the drive tires. These calculated values were compared with the corresponding measured in order to assess what model best estimated experimental data. In such a way, that pairs of corresponding measured and calculated data were statistically compared by the coefficient of determination $\mathbf{R^2}$ and standard error of the estimate $S_{Y.X.}$ For all cases, Y were calculated data and X the measured data. These statistical calculations were made with the statistical functions of the spreadsheet.

The 86 observations (not listed) can be grouped in the following ways:

• According to the traction mode:

Group 1: 78 observations in 2WD mode

Group 2: Eight observations in 4WD mode (FWA) (Front Wheel assist Drive)

• Depending on the consistency of the soil (and for 2WD):

Group 3: 67 observations[1] in the field was not muddy, 11 observations[2] are removed when the ground was muddy

• Depending on the surface condition of the ground (for 2WD and soil without mud)

Group 4: 48 observations on terrain without vegetation cover, 19 observations on terrain with vegetation cover (pasture, range)

The above data groups were formed to take into account the particular constraints and restrictions of each model according to the conditions that best applies in each model along to its authors and as was noted in the literature review. It should be remembered that:

- Model 1 (Wismer and Luth) does not apply in muddy soils (IC <150 kPa)
- Model 2 (Brixius) does not apply to soils with IC <300 kPa and apparently does not apply to soil with vegetable cover
- Model 3 (Evans , Clark and Manor) applies only in soils with vegetable cover
- Model 4 (Gee - Clough, McAllister , Pearson and Evernden) uses correction factors for tires with high lugs for example, which were used in the 11 observations in that type tires R2 were used. However, the authors caution that their model would not apply on firm soils with vegetable cover that would have better traction than estimated and not apply in muddy soils with poorer traction condition than estimated.

From the above were fixed the following 18 cases of comparison:

Case 1: M1 - G 1 **Case 5:** M 2 - G 1
Case 2: M 1 - G 2 **Case 6:** M 2 - G 2
Case 3: M 1 – G 3 **Case 7:** M 2 - G 3
Case 4: M 1 - G 4 **Case 8:** M 2 - G 4
Case 9: M 3 - G 1 **Case 13:** M 4 - G 1
Case 10: M 3 - G 2 **Case 14:** M 4 - G 2
Case 11: M 3 - G 3 **Case 15:** M 4 - G 3
Case 12: M 3 - G 5 **Case 16:** M 4 - G 4
Case 17: M 5 - G 1
Case 18: M 5 - G 2

*Each case represents a combination of the group of observations with the model used.

3 Results and discussion

3.1 General evaluation

Table 1 shows the fit between draft force and slip calculated from the models and the same that were measured in field tests selected. It can be analyzed collectively all cases. There are four cases in which it was not possible to make this adjustment for slippage (cases of

[1] Tires were used with middle lugs (about 35 mm in height) R1 type

[2] Tires were used with high lugs (75 mm) type R2

78 observations 2WD with each empirical models), since no logical data was obtained on some observations calculated with models.

Table 1 Fitting of traction parameters: Draft force and slippage measured in field experiments and calculated through traction models evaluated.

	Draft Force: FT		Slippage: D	
	R^2 (%)	S_{yx} *(kN)*	R^2 (%)	S_{yx} *(%)*
Case 1	43,7	*6,15*	----	----
Case 2	50,8	*4,02*	40,1	*11,02*
Case 3	72,6	*3,72*	7,3	*6,12*
Case 4	51,0	*4,14*	9,7	*6,42*
Case 5	41,4	*7,03*	----	----
Case 6	7,6	*3,08*	40,3	*6,06*
Case 7	87,3	*2,56*	39,3	*3,14*
Case 8	76,6	*2,90*	25,2	*3,20*
Case 9	41,3	*5,22*	----	----
Case 10	2,2	*2,57*	42,6	*8,12*
Case 11	82,3	*2,23*	41,4	*5,27*
Case 12	93,5	*1,45*	27,1	*4,63*
Case 13	89,5	*2,28*	----	----
Case 14	10,5	*3,08*	43,0	*4,23*
Case 15	**96,3**	***1,35***	**62,4**	***3,58***
Case 16	**96,7**	***1,06***	**65,1**	***2,06***
Case 17	87,2	*2,98*	17,0	*5,53*
Case 18	56,8	*7,33*	35,8	*5,23*

Table 1 globally highlights two facts: the models do not fit to the eight observations corresponding mode 4WD (assisted front traction) and Model 4 (Gee - Clough, McAllister, Pearson and Evernden) fits quite well with the experimental data 2WD mode.

In order to verify quality adjustment of each model to estimate the traction behavior and according to the scope and restrictions of these models, it was proceeded to the grouping of results by conditions.

3.2 Tractors in 2WD mode (Group 1)

All cases of resistance of soil and surface ground condition are included in order to evaluate the way of how each model is adjusted to any situation in the field regardless of the constraints that might arise in each model.

Figures 1 and 2 show the correlation obtained between the calculated draft forces for Models 4 and 5 (Gee - Clough, McAllister, Pearson and Evernden) and (Bekker) respectively and experimentally measured draft forces. From Table 1, it is clear that only Models 4 and 5 fit well. Special mention must be made to the Model 4, it makes a good estimate of draft forces measured from the parameters of the tractor, the tires and particularly with only one soil parameter (index Cone) compared to Model 5 where it was precise to use six soil resistance parameters, all estimated from the literature review .

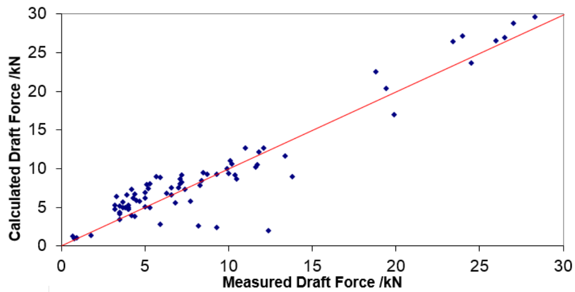

Figure 1 Correlation between draft forces calculated using Model 4 (Gee - Clough, McAllister, Pearson and Evernden) and measured draft forces for all 78 experimental observations of tests tractors 2WD mode. Case 13

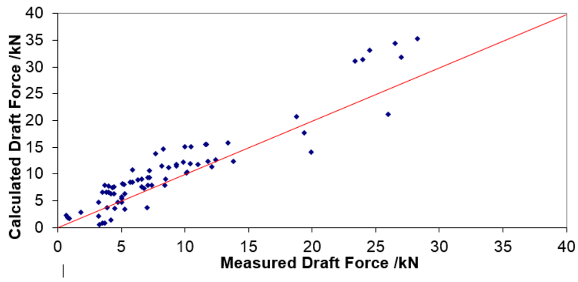

Figure 2 Correlation between draft forces calculated using Model 5 (Bekker) and measured draft forces for all 78 experimental observations of tests tractors 2WD mode. Case 17

Although explicit mention has been made about inapplicability of models (except 5) in regard of very poor or difficult terrain traction conditions, (appearing in 11 observations as discussed below), only model 4, including these difficult conditions, obtains a pretty good fit. Undoubtedly, the correction factors recommended by the authors, in particular concerning the situation of tires with high lugs (type R2) compared with mid lugs tires (type R1), allows to estimate a more approximate operation traction under such conditions. Comments about that are explicit in Elwaleed et al. (2006a) and Elwaleed et al. (2006 b) with respect of Models 1 and 2 and their little applicability to estimate the traction behavior with high lugs tires type R2.

Anyway, it was observed that the models 1 to 4 notoriously underestimated draft forces on 9 observations where measured IC was particularly low i.e. less than 122kPa. Only the Model 5 (Figure 2) in which the traction estimate is not based on the IC, but estimated support indexes, this underestimation not appear in poor traction conditions. In other words, Models 1-3 (remember that these three models have the same origin, that is, the American school of empirical equations based on the analysis of “traffic ability " of the US Army Engineer Waterways Experiment Station - WES) are very sensitive to poor traction conditions expressed by Index Cone parameter.

Schlosser et al. (2001) already had stated that Models 2 and 4 performed better estimates than Model 1. Even though it must be recognized that the authors of models 1 and 2 explicitly warn that proposals are not applicable to soils with IC < 200-300 kPa, as verified in Wismer and Luth (1974) and Brixius (1987) respectively. Schlosser et al. (2001) quoting Cervantes (1993) and Hernández (1999) reinforced in any case that Method 1 is very sensitive to the values of IC.

Also, Keen et al. (2013) note that now there is not a model to estimate traction in clayey soft, or saturated soils and variable moisture content in the soil profile, soil wetting and drying cycles, as well as the difficulty in measuring their mechanical properties, are serious difficulties in modeling traction.

Regarding reverse the estimation, no draft force depending on the parameters of tire, tractor, soil slippage, but estimate slippage in terms of the parameters of tire, tractor, soil and draft force could only be made for Model 5 since with difficult traction conditions, all other models could not logically estimate the values of slippage.

3.3 Tractors 4WD mode (Group 2)

If the traction performance is compared, only 8 observations that tractors were taken into 4WD mode (FWA), i.e. with assisted front traction, it can be noted that no model presents an acceptable estimate, according to the low coefficient of determination that said no model explains beyond 57% of the draft force or slippage behavior. Suggesting that although measurements were reported as 4WD mode (FWA), it is probably that tractors were not connected the control of double traction. It should be noted that given the small number of observations available for 4WD, it is inappropriate to make any kind of comparison between models, and certainly suggests making more experimentation.

3.4 2WD tractors without observations with difficult terrain traction conditions (Group 3)

With the remaining 67 observations, all models improve traction estimation (it has been excluded from this analysis model 5). Although Model 2 (Brixius) was derived from Model 1 (Wismer and Luth) it’s also noted that traction estimation was improved by adding new coefficients and the inclusion of a new term in function of the slippage for the rolling resistance coefficient.

Dias Acuna et al. (1995) also used the model 1 (Wismer and Luth) to evaluate the quality of traction estimation with a 4WD tractor (FWA) but with front traction disconnected, clayey soils about IC 800-1200 kPa and rear tires 18.4 -34 with diagonal plies, i.e. conditions quite similar to some of those provided in Group 3, and obtained a correlation coefficient, R, of 0.74 between the draft forces measured and calculated, and these authors appreciated that this method was suitable to estimate the draft forces in tires tractors. In the present work a coefficient of determination of 73% (R≈0, 85) was obtained and it can be assessed as an acceptable estimate, but certainly less than the other three models. This is consistent with what was found by Schlosser et al. (2001), in which the Brixius and Gee-Clough et al models obtained better estimates of the traction behavior compared to the Wismer and Luth model.

It is also clear that model 4 (Gee - Clough and collaborators) has the greatest potential to estimate the traction behavior in 2WD tractors and without considering the worst traction conditions (which are conditions not recommended for agricultural machines traffic and in which soil properties can be seriously degraded) .

Therefore it can be highlighted the very good fit obtained with the model 4, also that the model 3 (Evans et al.), which was developed for land with vegetation cover, presents an underestimation of draft forces calculated, precisely because their coefficients were obtained for better traction conditions .

Figure 3 shows the comparison between the slippage calculated and those measured for model 4 (Gee - Clough, McAllister, Pearson and Evernden) and this model presented the best quality estimation of slippage parameter, with a prediction up 62%.

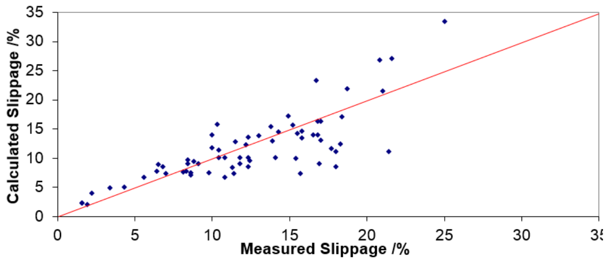

Figure 3 Correlation between the calculated slippages using Model 4 (Gee - Clough, McAllister, Pearson and Evernden) and measured slippages in the 67 observations that tractors were in 2WD mode without difficult muddy soils. Case 15

3.5 2WD tractors without observations in terrains with difficult traction conditions and without observations in soils with vegetable cover (Group 4)

This grouping obeys that soils with vegetable cover the traction behavior is different. If this cover is dry, that behavior can be improved and conversely, if it is wet .things may get worse. Evans et al. (1991) developed the coefficients of its model (Model 3) and explicitly indicate this situation by comparing it with model 2 (Brixius). Clark and Van de Linde (1993) also suggest that in Model 1 (Wismer and Luth) it could be adjusted the coefficients of the equations to better suit covered surfaces. Meanwhile Gee- Clough (1980) admits that grassland fields should enable a better behavior than the estimated traction with its Model 4.

If the values of the coefficients of determination for fitting experimental parameters for Group 3 and Group 4 are compared, it is clear that no improving of the estimate was obtained. The reason for this could be the moisture content of the soil and pasture at the time of the tests. Such information is not available; therefore it is not possible to give a conclusive explanation. In fact, Models 1 and 2 worsened its estimate while the Model 4 improved slightly its prediction. Anyway it is clear that Model 4, again, is the model that better estimates the experimental behavior of traction.

3.6 2WD tractors without observations in terrains with difficult traction conditions and only with observations in soils with vegetable cover (Group 5)

In order to evaluate specifically the Model 3 (Evans , Clark and Manor) because it was developed particularly to estimate the behavior of traction in areas with vegetation cover (pastures) possibly dry , Group 5 was formed, including only 19 observations in this type of terrain (of course were conducted with 2WD tractors and in good traction conditions) . It was found indeed that this model estimates pretty good traction in soils with vegetable cover. As for the slippage parameter, the same situation is verified by comparing the normal error of the estimate, but not with the coefficient of determination.

3.7 General comments and recommendations for use.

After it was accomplished a full analysis of the quality of the estimate made by the five models evaluated for each of the conditions of surface soil condition, it became clear that the model No. 4, developed in the English School by Gee- Clough and collaborators, presented the best estimate of the behavior of tractors in all traction conditions of the ground on which the tests were conducted. Similarly, the model developed by Evans and collaborators showed a good estimate for specific cases where traction is made on surfaces covered with pasture or grassland.

A special comment deserves the semi-empirical model established by Bekker from considerations of strength and support soil parameters considering a partially state of stresses within the tire-soil interface, in the sense that if these parameters are available, it could be achieved quite acceptable estimates and with the added advantage of providing an initial diagnosis of the state of stress in the ground, which certainly could be used to link to more formal studies of the effect of traffic tractors on agricultural soils.

Now, once you have a reliable traction model, the question is: For what would be used in practice of the tractor operation in the field?

Surely the answer is related with the prediction of traction behavior of the tractors in the field without appealing to trial and error experiments that in most situations would be not only very expensive but require too much time. Moreover, it is known that the traction behavior is complex and depends on many variables which further complicates the development of experimental procedures.

With a good traction model it can be cleared up unknowns such as:

- For specific field situations which traction mode: 2WD, 4WD (FWA) or 4WD would behave better?

- What would be the best axle weight settings for each of these modes of traction, as well as the needs of ballast according to the types of used tires, power available and certainly the ground condition?

- What are the tire sizes (in terms of diameters and widths) most suitable in accordance with the type of surface condition, weights and ballast available, output power and of course, to required draft implement?

- What kind of tires, if diagonal plies or radial plies, would be more efficient; which would be the appropriate inflation pressures depending on the tire load and the soil type?

- Recommendations could be established regarding improved traction obtainable from configurations with dual tires or 'tandem'

- What would be the set of recommended tires, ballast and operating speeds to achieve maximum efficiencies of traction, which ultimately shows the best relationship between delivered work and energy fuel consumed?

And so, it might be proposed several options for handling traction variable under various soil and labor conditions to be done in the field. Clearly with a traction model, the effects can be individualized for each of the parameters on the overall traction performance to give appropriate recommendations, and all possible combinations of such parameters in order to obtain the best results in regarding efficient energy use delivered by these vehicles.

Interesting examples of such practical field applications arising from the use of traction models and associated software can be seen in the work of Gee-Clough (1980), Dwyer (1984) , Grisso et al. (1992) Al-Hamed et al (1994), Zoz and Wiley (1995), Al- Hamed and Al- Janobi (2001) , Zoz and Grisso (2003), Catalan et al (2008) , Pranar and Pandey (2008) , Sahu and Raheman (2008), Kumar and Pandey (2009) , Tiwari et al. (2010) and Kolator and Bialobrzewski (2011) .

4 Conclusions and recommendation

• The model developed in the traction NIAE in England by Gee- Clough, McAllister, Pearson and Evernden showed the best fit (R^2 of 89 %) to the experimental values in field trials conducted in this country for several years, by the Colombian Agricultural Institute. This model estimated pretty well about the traction behavior of various kinds of tractors with several supplies of tires and loads and throughout the whole soil conditions, typical of various agro-ecosystems in the country.

• It was confirmed that difficult muddy soil conditions (perhaps undesirable) from the viewpoint of traction are the most complicated to predict. In fact the use of tires type R2 (cane or rice) could only be acceptably estimated with model Gee- Clough , due to correction factors proposed for tires with high lugs.

• If such poor conditions are discarded, most of the evaluated models showed an acceptable fit, but again the British model reached the best estimate with an excellent coefficient of determination (R^2 of 96%).

• The semi -empirical model of Bekker provided a good estimate but presented the drawback of requiring support soil parameters, difficult to measure in the field.

• For traction conditions with pasture or grassland cover, the American model of Evans and colleagues (certainly derived from models Wismer and Luth and Brixius) got a very good fit, which would make it advisable to estimate traction in this type of surface.

• It is recommended to perform a complete test scheme of tractors in 4WD mode to make a better evaluation of these models in such conditions.

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