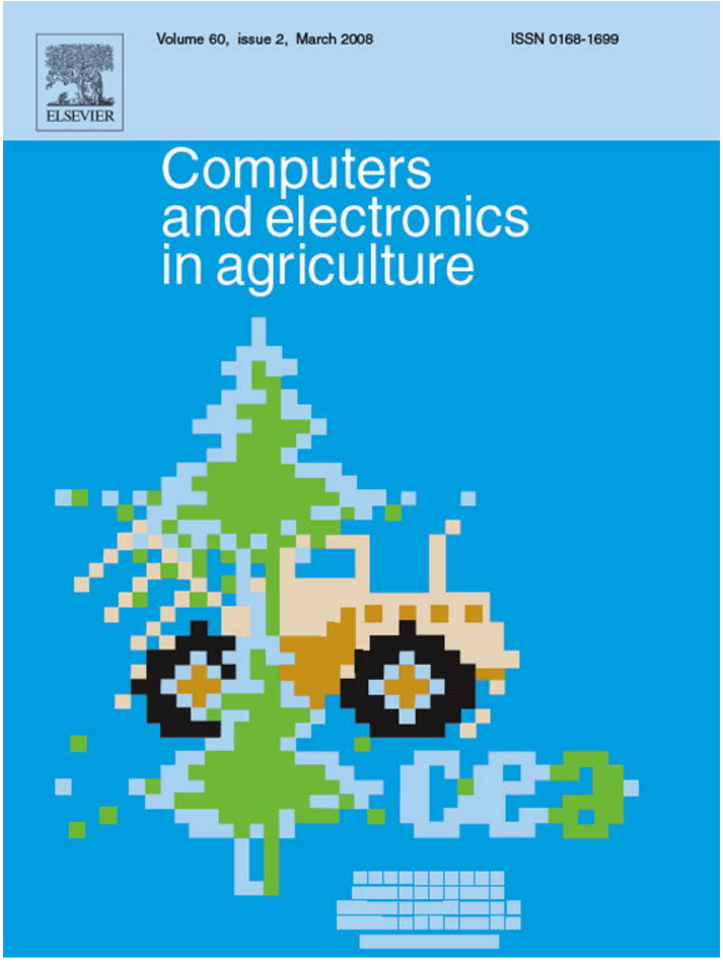
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Short communication

Tractor_PT: A traction prediction software for agricultural tractors

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ABSTRACT

Traction prediction modelling, a key factor in farm tractor design, has been driven by the need to find the answer to this question without having to build physical prototypes. A wide range of theories and their respective algorithms can be used in such predictions.

The "Tractors and Tillage" research team at the Polytechnic University of Madrid, which engages, among others, in traction prediction for farm tractors, has developed a series of programs based on the cone index as the parameter representative of the terrain. With the software introduced in the present paper, written in Visual Basic, slip can be predicted in two- and four-wheel drive tractors using any one of four models. It includes databases for tractors, front tyres, rear tyres and working conditions (soil cone index and drawbar pull exerted). The results can be exported in spreadsheet format.

1. Introduction

Computerized tractor simulation and prediction models, which economize on time and field trials, constitute an essentially cost-free approach to the determination of the relative importance of a number of factors affecting actual tractor operation. Gradually but steadily rising energy prices oblige engineers and users to improve tractor operation by comparing and analyzing the various parameters involved. Tractor performance on actual soil conditions differs substantially from the results of laboratory track testing. The physical laws governing movement and behaviour in general vary from one surface to the other, while constant changes in terrain and drawbar pull generate ongoing variations in the dynamic load on each wheel.

The soil–vehicle interface is the primary cause of low traction efficiency (estimated to be on the order of 60% on farmland, for transmission performance of nearly 90%). In 1935 the National Tillage Machinery Laboratory at Auburn, Alabama, was created (Bekker, 1969). The soil bins built there to test farm implements soon proved to be a valuable tool for analyzing soil response to the mechanical stress caused by ploughing vehicles and implements. The Vicksburg, Mississippi Waterways Experiment Station (WES) was designated to launch a trafficability programme in 1945. In the 1950s, a host of papers dealing with vehicle behaviour on natural terrain appeared, scattered across a variety of journals (Upadhyaya et al., 1997). Bekker's studies on the occasion of the NASA moon flight programmes fathered TERRAMECHANICS. Many surveys have been based on strain-deformation relations at

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the soil–vehicle interface, such as the Nepean Tracked Vehicle Performance Model (NTVPM) (Wong, 1986).

Deere & Co. implemented a vast experimental programme to analyze the conditions defining maximum traction performance in farm tractors, using the cone index as the sole parameter to represent the terrain. A series of associated parameters were likewise employed, such as wheel number (Wismer and Luth, 1972) and mobility number (Brixius and Wismer, 1975). In England, the National Institute of Agricultural Engineering (NIAE, Silsoe) studied the traction capacity of farm tyres using vehicles such as the single wheel tester and developed a theory likewise based on the cone index (Gee-Clough et al., 1978; Gee-Clough, 1984).

Computer models or simulation software to predict tractor response contribute to determining the relative importance of different factors that affect soil–tractor behaviour without the need for costly and time-consuming field trials. Moreover, this software helps researchers and tractor manufacturers to improve performance. Al-Hamed et al. (1994) introduced a spreadsheet to calculate tractive efficiency in radial wheels. Subsequently used by authors such as Grisso and Zoz (2004), Zoz and Grisso (2003) and Goering and Hansen (2004), it has gradually evolved into a system that covers the entire tractor. Simulation software to predict tractor performance may draw from different programming tools. Presently Visual Basic and Visual C++ are widely used to develop such software. The Visual Basic environment facilitates user access to and implementation of program functionalities. Al-Hamed and Al-Janobi (2001) developed prediction software that calculates drawbar pull and slip from engine power and theoretical forward speed.

The "Tractors and Tillage" research team at the Polytechnic University of Madrid, which engages, among others, in traction prediction for farm tractors, has developed a series of programs based on the cone index as the parameter representative of the terrain. With the software introduced in the present paper, written in Visual Basic, slip can be predicted in two- and four-wheel drive tractors using any one of four models. It includes databases for tractors, front tyres, rear tyres and working conditions (soil cone index and drawbar pull exerted). The results can be exported in spreadsheet format.

2. Traction prediction models

Fig. 1 represents the general outline for traction prediction models. The input data refer to the vehicle, terrain and working conditions (drawbar pull exerted).

The models used yield an exponential equation that relates traction coefficient and slip as follows:

$$\mu = \mu_{\max}(1 - e^{-\alpha\delta})$$

where δ is slip, α is a parameter that characterizes the soil–vehicle system, μ is the traction coefficient ($\mu_{\max}$ is the maximum traction coefficient).

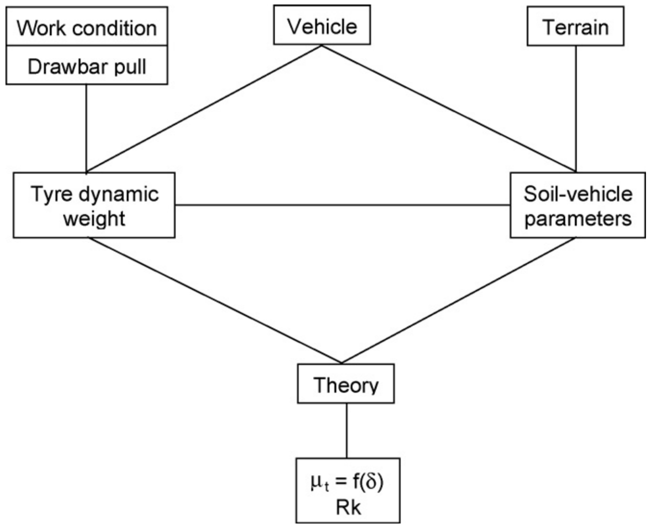


Fig. 1 – Traction prediction theory flow diagram.

3. Models used

As a difference with other prediction software programs, Tractor_PT deploys the four prediction models characterized in Table 1, all of which use the cone index to represent soil conditions. The first three are well known: the ASAE or Cn (Wismer and Luth, 1972); Deere or Bn (Brixius and Wismer, 1975); and NIAE or MN (Gee-Clough, 1984) models. The fourth, the modified Cn (ASAE) model, was developed by the Polytechnic University of Madrid's Rural Engineering Department based on years of comparative studies of predicted and experimental testing.

Program output consists of two- and four-wheel drive tractor slip values for the four prediction theories. For greater convenience, the software is provided in Spanish, Portuguese, English or French. Before predictions can be processed, the input values must be entered into four databases: tractor, test conditions (cone index and drawbar pull exerted), rear tyres and front tyres.

The primary difference between this software and the Grisso-Zoz Goering spreadsheet and Al-Hamed and Al-Janobi program lies in the input data. Tractor_PT uses drawbar pull rather than engine horsepower.

4. Modified ASAE model

The Madrid School of Agricultural Engineering's Rural Engineering Department has engaged in terramechanics research (or land locomotion) since 1970. Linares et al. (1993), testing tractors under actual field conditions based on electronic instrumentation able to record test variables *in situ* (Camps et al., 2000a; Catalán and Linares, 1998). With these facilities, comparisons could be drawn between prediction and experimentation, applying cone index-based theories.

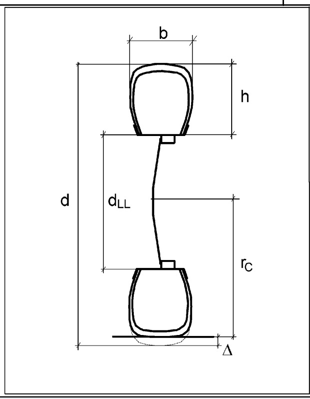
In these surveys, predictions were made on a LOTUS spreadsheet. When the Cn theory was used, the comparison revealed deviations: the theory proved to be pessimistic for soft soils (with higher predicted than experimental figures)

Table 1 – Prediction models used in the Tractor_PT program

Model	S-V parameter	Rolling resistance coefficient, k	Gross thrust coefficient, μ_t
Cn	Wheel number $C_n = \frac{CI \cdot b \cdot d}{Pr}$	$k = \frac{1,2}{C_n} + 0,04$	$\mu_t = 0,75 \cdot \left(1 - e^{-0,3 \cdot C_n \cdot \delta}\right)$
Bn	Mobility Number $B_n = C_n \cdot \frac{1 + 5 \cdot \frac{\Delta}{h}}{1 + 3 \cdot \frac{b}{d}}$	$k = \frac{1}{B_n} + 0,04 + \frac{0,5 \cdot \delta}{\sqrt{B_n}}$	$\mu_t = 0,88 \cdot \left(1 - e^{-0,1 \cdot B_n}\right) \cdot \left(1 - e^{-7,5 \cdot \delta}\right) + 0,04$
MN	Mobility number $MN = C_n \cdot \sqrt{\frac{\Delta}{h}} \cdot \frac{1}{1 + \frac{b}{2 \cdot d}}$	$k = 0,049 + \frac{0,289}{MN}$	$\mu_t = \mu_n + k$ $\mu_n = \mu_{nmáx} \cdot \left(1 - e^{-k' \cdot \delta}\right)$ $\begin{cases} \mu_{nmáx} = 0,796 - \frac{0,92}{MN} \\ k' \cdot \mu_{nmáx} = 4,838 + 0,061 \cdot MN \end{cases}$
Modified Cn	$C_n = \frac{CI \cdot b \cdot d}{Pr}$	$k = \frac{1,2}{C_n} + 0,04$	$\mu_t = 0.75 \cdot \left(1 - e^{A_1 \cdot Cn \cdot \delta}\right)$ Theoretical radii : $A1^* = \frac{253}{CI^{1,09}}$ Experimental radii : $A1 = \frac{182}{CI^{1,0231}}$

$Pr \rightarrow$ tyre weight
$b \rightarrow$ section width
$d \rightarrow$ overall diameter
$\delta \rightarrow$ slip

$$\begin{cases} \Delta = \left(\frac{d}{2} - r_c\right) \cdot \frac{P_r}{P_{rmáx}} \\ h = \frac{d - d_{LL}}{2} \end{cases}$$



$b \rightarrow$ tyre section width
$d \rightarrow$ overall diameter
$\Delta \rightarrow$ tyre deflection
$h \rightarrow$ tyre section height
$d_{LL} \rightarrow$ rim diameter
$r_c \rightarrow$ static loaded radio (with max. load per wheel on hard soil
$P_{rmáx} \rightarrow$ maximum tyre load
$P_r \rightarrow$ tyre load
$CI \rightarrow$ Cone Index (kPa)

and optimistic for hard soils. An adjustment between prediction and experiment was made, maintaining the original equation that related traction coefficient μ_t to slip δ:

$$\mu_t = 0.75(1 - e^{A1Cn\delta})$$

In the original model A1, the value was 0.3. For the adjustment, Cervantes (1993) proposed 0.16 for hard soil and 0.61 for soft soil.

Further comparisons were made with four-wheel drive tractors on hard and soft soil. DOS software titled TRACCIÓN (Catalán, 1996) was used to calculate the predictions. The pattern found was the same as in the two-wheel drive tests and the fit between the experimental and predicted results was improved by changing the parameters.

This consistency in the results obtained prompted the initiation of a study that attempted to expand the range of soils tested from 200 to 1200 kPa, although for theory Cn and two-wheel drive vehicles only (Hernández, 1998). In light of the results of that study, a change was proposed in the slip coefficient in the original Cn theory, to be replaced by slip-dependent parameter A1 (Table 2). This led to a substantial improvement in the comparison between predicted and experimental findings. In this case, prediction was conducted with an Excel spreadsheet, using the radii measured in the experimental trials (Cervantes et al., 2000). The same operating procedure was deployed in subsequent years, using "catalogue" radii for the prediction (Catalán and Linares, 1998; Camps et al., 2000b) obtaining the $A1^*$ parameter (Table 2). The software developed for this purpose, written in C++, was named MITRA (Spanish acronym for farm tractor modelling software) (Camps et al., 2005).

The problems encountered to export the results obtained with MITRA software hindered its dissemination, however. A stage in which the effect of tyre weight and width on tractor performance was studied with a Mathcad spreadsheet (Mahl

Table 2 – Parameter A1 used in modified Cn model

Radii	Parameter
Measured in experimental tests	$A1 = \frac{182}{CI^{1.0231}}$
Theoretical (catalogue)	$A1^* = \frac{253}{CI^{1.09}}$

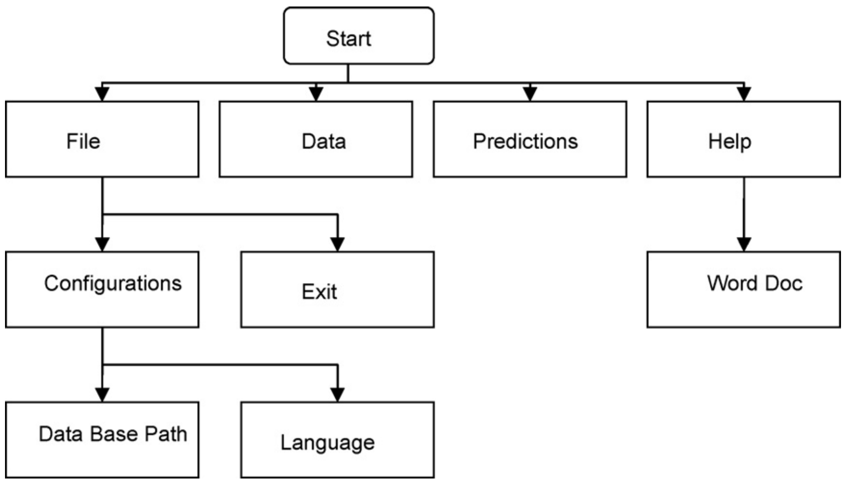


Fig. 2 – Tractor_PT program structure.

et al., 2005; Linares et al., 2005) was followed by the development of new prediction software, Tractor_PT (Linares et al., 2006).

5. Tractor_PT program structure

Object-oriented programming is flexible and easy to use. For this reason, the program for predicting traction in 2WD and 4WD tractors on farm land was developed in Visual Basic 6.0. TRACTOR_PT has a Windows graphic user interfaced (GUI) developed in Visual Basic, Access to store the data model and Excel as interface to print form and to export data. It runs on computers with Windows 98/NT/2000 or XP operating systems and Microsoft Office Access, Word and Excel. The program has two Access data base files, one to store the parameters depending on the language selected. All the fixed text is stored in this database, the windows labels, the pop-up message texts, the Excel form texts, and the dropdown list options. The program can manage four languages (English, French, Portuguese and Spanish), but languages can be added to the database without modifying

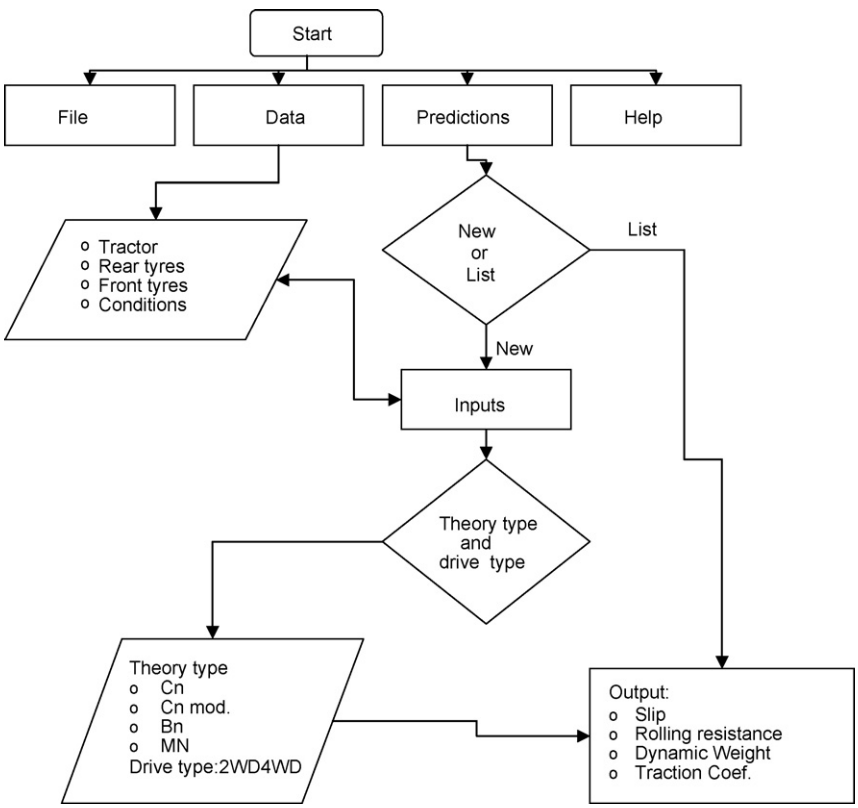


Fig. 3 – Tractor_PT program operation procedure.

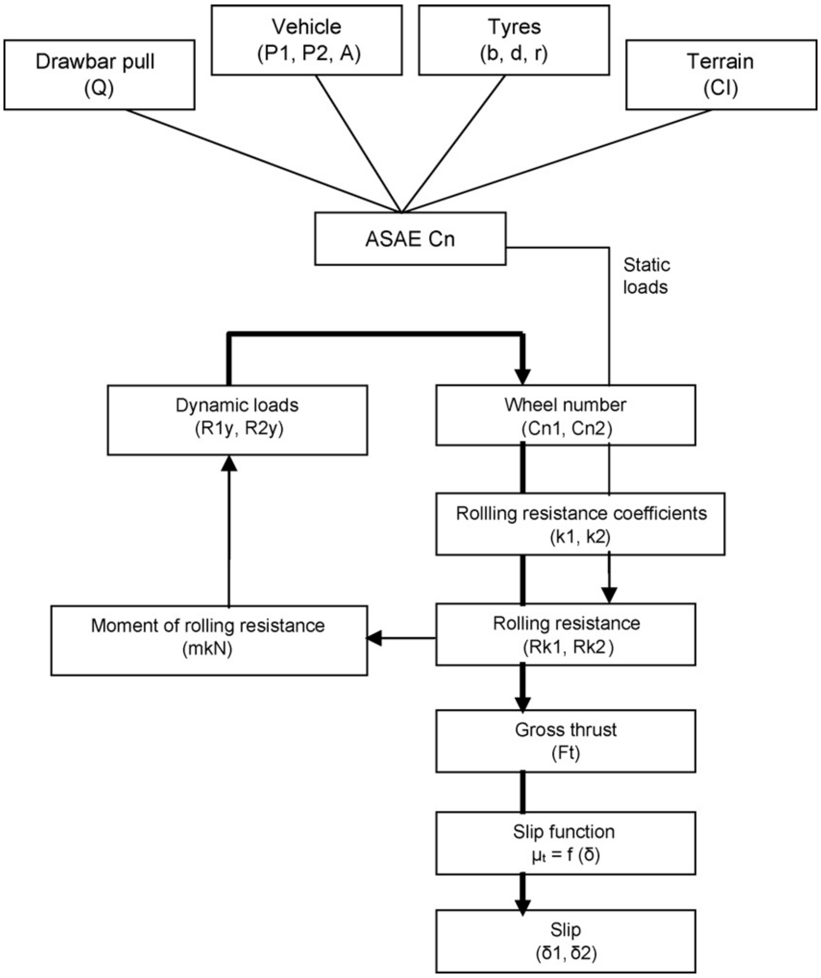


Fig. 4 – Calculation flow chart for ASAE theory, MFWD:4WD.

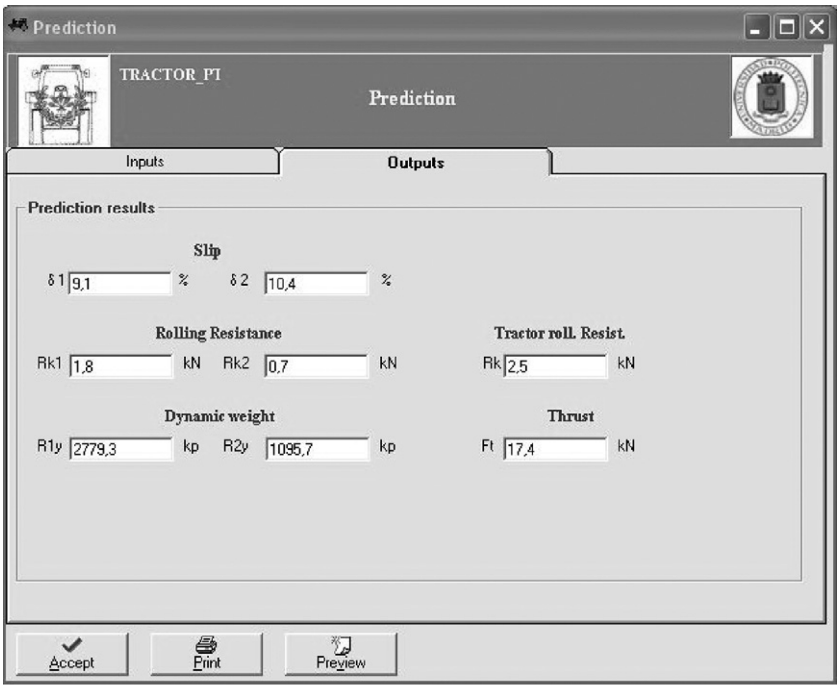


Fig. 5 – Summary screen showing results obtained.

the hard code in the Visual Basic modules (Linares et al., 2006).

In the other database the user stores the prediction data using the Visual Basic GUI. This database has five tables, conditions, tractor, rear tyres, front tyres and predictions. The GUI is very easy to manage and is perfectly integrated with the Windows utilities and programs. It uses the Newton iteration algorithm to obtain the root of the slip function.

The software covers two- and four-wheel drive tractors working on horizontal terrain with parallel-horizontal drawbar pull. All other conditioning factors are defined by the prediction theories used.

The program flow chart is given in Figs. 2 and 3. The data sheet and prediction menus are accessed from the main menu, to create the databases relating to the tractor, front and rear tyres and test conditions. The user may create, correct, add or remove data sheets from any of the databases.

To predict the performance of a given tractor, the user selects "new prediction" on the "predictions" submenu to display the screen where the respective data, including the choice of drive (two- or four-wheel) and model, are to be entered. The calculation procedure for a 4WD tractor using model Cn is outlined in Fig. 4. Prediction results can be visualized both on a summary screen (Fig. 5) or as a preview (Fig. 6) and exported to a spreadsheet.

TRACTION PREDICTION IN AGRICULTURAL TRACTORS

Theory		MN MFWD/4WD Tractor			
Reference		**KUBOTA M1-100-NT-1-ND-4-CON-1-MN-MFWD/4WD**			
Tractor					
Reference	**KUBOTA M1-100**				
Model	**M1-100 DT E(4WD)**				
Static rear axle weight (kp)	p1	2.375	Static front axle weight (kp)	p2	1.500
Total weight (kp)	Pt	3.875	Drawbar height (m)	hq	0,5100
Wheelbase	l	2,4400	Center of Gravity Abscissa (m)	ag	0,9445
Inter axle ratio	RM	1,4162	lead	a	1,0135
TYRES					
FRONT TYRES			**REAR TYRES**		
Reference	**NT-1**		Reference	**ND-4**	
Model	**18,4R38**		Model	**18,4R38**	
Maximum Vertical tyre load (kg)		3.000	Maximum Vertical tyre load (kg)		1.700
section width (m)	b1	0,4670	section width (m)	b2	0,3750
Rim Diameter (in)	dll1	38	Rim Diameter (in)	dll2	24
Rim Diameter (m)	dll1	0,9652	Rim Diameter (m)	dll2	0,6096
overall tire diameter (m)	d1	1,7420	overall tire diameter (m)	d2	1,2380
static loaded radius (m)	r1c	0,7970	static loaded radius (m)	r2c	0,5580
Tire rolling radius (m)	r1	0,8300	Tire rolling radius (m)	r2	0,5940
WORKING CONDITIONS					
Reference	**CON-1**				
Drawbar Pull (kp)		1.520			
Cone Index (kPa)		1.043			
CALCULATION WITH STATIC WEIGHT					
Wheel Number	Cn1	72,8361	Wheel Number	Cn2	65,8121
Tyre Deflection	Δ1	0,0740	Tyre Deflection	Δ2	0,0610
Modified tyre deflection	Δm1	0,0293	Modified tyre deflection	Δm2	0,0269
Mobility Number MN	MN1	17,6380	Mobility Number MN	MN2	16,7274
Coefficient of rolling resistance	k1	0,0654	Coefficient of rolling resistance	k2	0,0663
Rolling resistance (kN)	Rk1	1,5	Rolling resistance (kN)	Rk2	1,0
Tractor rolling resistance (kN)	RKV	2,5			
Moment of rolling resistance (mkN)	MK	2,1			
CALCULATION WITH DYNAMIC WEIGHT					
Dynamic rear axle weight (kp)	R1Y	2.779,3	Dynamic front axle weight (kp)	R2Y	1.095,7
Wheel Number	Cn1	62,2397	Wheel Number	Cn2	90,0998
Tyre Deflection	Δ1	0,0740	Tyre Deflection	Δ2	0,0610
Modified tyre deflection	Δm1	0,0343	Modified tyre deflection	Δm2	0,0197
Mobility Number MN	MN1	16,3046	Mobility Number MN	MN2	19,5721
Coefficient of rolling resistance	k1	0,0667	Coefficient of rolling resistance	k2	0,0638
Rolling resistance (kN)	Rk1	1,8	Rolling resistance (kN)	Rk2	0,7
Tractor rolling resistance (kN)	RKV	2,5			
Gross thrust (kp)	Ft	1.775,3			
wheel slip (%)	δ	**9,1**	**wheel slip (%)**	δ2	**10,4**

Fig. 6 – Full prediction results, exportable to Excel spreadsheet.

6. Conclusions

A computerized model in Visual Basic has been developed to predict 2WD and 4WD:MFWD tractor performance on farmland. The model is designed for use in education and research. The menus and windows guide the user through a series of fairly easy steps. The interface is intuitive and user-oriented with screens for selecting the type of tractor, tyres and conditions.

The software uses four prediction models that calculate dynamic axle load, soil–vehicle parameters and slip from the drawbar pull.

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