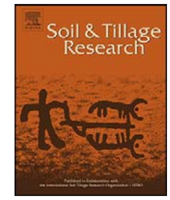
Soil & Tillage Research 110 (2010) 236–242

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still



Applications of empirical methods in central Italy for predicting field wheeled and tracked vehicle performance

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ARTICLE INFO

Article history:
Received 3 November 2009
Received in revised form 28 July 2010
Accepted 4 August 2010

Keywords:
Wheeled tractor
Tracked tractor
Soil cone index
Predicting wheeled vehicle performance
Predicting tracked vehicle performance
Central Italy

ABSTRACT

Due to the agricultural field traffic and to the soil tillage implements, soil compaction has been recognised as a severe problem in mechanized agriculture and has an influence on many soil properties and processes. In this paper, empirical methods originally developed by the different Authors at Waterways Experiment Station (WES) for predicting the performance of off-road vehicles were applied on agricultural soil. The models considered and based on soil–vehicles interaction were: clay–tire rubber track numeric ($N_{c,r}$), mobility index (MI), vehicle cone index (VCI), mean maximum pressure (MMP) and they included besides soil strength, the load carried by the tire or track, some technical characteristics of the tire or track of the vehicle, as well as the number of passes on the same track. These models have been validated with the tests results of a number of selected agricultural and forest vehicles over a range of soil in central Italy: Vertic Cambisol, Haplic Calcaric Cambisol and Eutric Cambisol. Significant correlations among the above indexes and among $N_{c,r}$ and two tire–track performance parameters: traction coefficient and traction efficiency, have been found. In addition a correlation between the measured cone index values during field tests, and the predicted cone index values have been developed.

Through the field data collected and the elaboration and validation of the indexes it was possible to frame in a coherent way, the performance of agricultural machinery of different mass and power, running gear system (wheels, tires with low aspect ratio, metal and rubber tracks, self-propelled for the harvest, transport and distribution of agricultural products), even though particular interpretative shrewdness was necessary in the application of such formulas in the cases of innovative machinery as with the rubber track system. The vehicles that have obtained the higher values of $N_{c,r}$ (>20) have obtained the lowest values of both the MMP (<156 kPa) and VCI (VCI_1 < 110 kPa; VCI_4 < 269 kPa). These vehicles have also obtained the higher values of traction coefficient (0.7–0.9) and of traction efficiency (0.74–0.8).

Agricultural field traffic is an important aspect of soil management and such indexes, based on parameters that determine the impact of the agricultural mechanization on soil qualities, can usefully be considered in the management of the agricultural farm to reduce soil compaction due to both the traffic of machinery and to tillage implements particularly when considering the aspect of altered land use.

1. Introduction

Soil compaction, due to field traffic and to soil tillage implements, has been recognised as a severe problem in mechanized agriculture and has an influence on many soil properties and processes and on crop yield (Soane and Van Ouwerkerk, 1995; Keller et al., 2002; Krümmelbein et al., 2008; Lipiec et al., 2009).

External forces applied to soil during land management interact with internal soil strength and can be used as a land use correction factor. Soil management strategies depend on the knowledge and applicability of science based recommendations which must be suitable under the given site conditions. With respect to the prevention of additional soil deformation and the corresponding soil degradation, it is obvious that all changes in soil properties induced in the past are permanent for at least several decades and no amelioration technique is able to recreate the original site properties within a short time. All soil, physical, mechanical, chemical and biological properties and functions need to be preserved for future generations, therefore to define site-specific boundary conditions for soil strength and the related physic-chemical soil properties it is necessary to maintain the properties particularly when considering the aspect of altered land use (Horn, 2009).

Furthermore, proper tillage can alleviate soil related constraints while improper tillage leads to a number of degradation processes, e.g., damage to soil structure, accelerated erosion, depletion of soil organic matter and fertility and decreasing of water movements,

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0167-1987/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.still.2010.08.009

organic carbon and plant nutrients (Ishaq et al., 2002). The soil conditions are also very important to limit the damage of compaction due to the traffic of the agricultural vehicle. Many studies indicate that soil damage increased on very moist to wet soil compared to dry soil, with the number of vehicle passes and with the increase in the tire or track ground contact pressure (Horn and Fleige, 2009; Mosaddeghi et al., 2009).

The condition of land for field operations can be classified in terms of trafficability and workability that is largely governed by the mechanical state of soil and its susceptibility to damage during machinery operations. Trafficability is concerned with the ability of soil to provide adequate traction for vehicles, and withstand traffic without excess compaction or structural damage. Workability is concerned with soil-engaging operations and can be considered to be a combination of trafficability and the ability of soil to be manipulated in a desired way without causing significant damage or compaction (Campbell and O'Sullivan, 1991). The most influential factor in determining the suitability of land for field operations is the soil moisture status. An indication of the mechanical state, and likely behaviour under load, can be gained from a range of soil properties including penetration resistance, shear strength, bulk density and plastic limit, the majority of which are strongly dependent on moisture status.

A number of researchers have developed trafficability and workability prediction models based on cone penetration resistance that measures the resistance of soil penetration of a standardized cone (cone index). The use of penetration resistance has a merit for providing a rapid assessment of soil mechanical condition on a given day and together with a dry bulk density (Dèfossez et al., 2003) and shear strength have also been used as parameters to measure vehicle–soil interaction since Proctor (1933) and Wismer and Luth (1973).

Cone index, can provide a convenient measure of soil strength and will vary not only with the size and shape of the probe but also with a range of soil properties including soil–metal friction, particle size distribution, water content, resistance to compression and shear strength, which includes both internal friction and cohesion. For field soils, these factors vary with bulk density, water content, structure and soil type. Where, only bulk density and water content vary, and over limited ranges, a linear relationship between resistance to cone penetration and water content may apply (Earl, 1997). Soil compaction and soil–machine interaction models are important tools for controlling compaction due to agricultural field traffic and to prevent soil erosion (Horn and Fleige, 2005). These models allow for a realistic estimation of the stresses at the tire–track soil interface that can be estimated from tire and track parameters (Keller et al., 2007).

The aim of this study was to apply, on agricultural soil, empirical methods originally developed by the different Authors (Freitag, 1965; Rula and Nuttal, 1971; Rowland, 1972, 1975; Tournage, 1978) at U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for predicting the performance of off-road vehicles and reported by Wong (1993). The indexes developed and based on soil–vehicle interaction were: clay–tire rubber track numeric ($N_{c,r}$), mobility index (MI), vehicle cone index (VCI), mean maximum pressure (MMP). Others objectives were: to validate the empirical models with the tests results of a number of modern selected agricultural vehicles over a range of soils in central Italy during field operations; to develop statistical correlation among the different indexes and among $N_{c,r}$ and two field performance parameters: traction coefficient and traction efficiency.

2. Materials and methods

2.1. Empirical methods for predicting wheeled and tracked vehicle performance on agricultural soil

The empirical indexes considered in this study ($N_{c,r}$, MI, VCI, MMP) included, besides the soil strength, the load carried by the tire or track, some technical characteristics of the tire or track of the vehicle (tire or track width, tire or track wheel diameter, unloaded tire section height, number of wheel station in one track, tire deflection, total length of the belt track, the track pitch) as well as the vehicle passes. They have been validated with the tests results of agricultural vehicles over a range of soil in central Italy and some characteristics of the soil are reported in Table 1 with FAO soil classified (FAO, 1998).

During the field tests, penetration resistance (CI) was measured both after vehicle passes and on the control areas, which had no traffic, using a self-recording electronic penetrometer (Eijkelkamp penetrologger) with a 60° cone and base area of 100 mm^2, driven into the soil at a constant rate (5 cm s^{-1}). Penetrometer readings were taken in the plough layer, in increments of 1 cm, to a depth of 0.40 m. Correlation between the measured cone index values during field tests and the predicted cone index values by means of a general equation was develop.

2.1.1. General equation for cone index predicted

General equation for cone index predicted in MPa function of water content of soil and specific weight was considered for a range of soil (Eradat Oskoui and Witney, 1982 part I; Eradat Oskoui et al., 1982 part II):

$$\mathrm{CI} = \frac{450.5}{w^2} + 0.019\gamma \tag{1}$$

where CI is cone index (MPa), w is water content of soil (kg 100 kg^{-1}), γ is specific weight (kN m^{-3}).

2.1.2. The clay–tire and rubber track numeric

To appraise the variation of the soil penetration resistance following the single or repeated passes of the vehicles in the surface layers (0–0.20 m depth), an empirical model based on two dimensionless prediction terms, or soil–tire numeric (Freitag, 1965; Tournage, 1978) has been considered. The clay–tire numeric represents the soil strength and load carried out on the tire or track.

The clay–tire numeric N_c for tires operating in purely cohesive soil (near-saturated clay) was defined as:

$$N_c = \frac{\mathrm{CI}bd}{W} \times \sqrt{\frac{\delta}{h}} \times \frac{1}{1 + (b/2d)} \tag{2}$$

Table 1
Some characteristics of the soil used in the traffic studies.

Property	kg (100 kg)$^{-1}$				
Sand (2000–50 μm)	8	17	60	8	35
Silt (50–2 μm)	52	48	13	22	33
Clay (<2 μm)	40	35	27	70	32
(USDA classification)					
Texture	Silty clay (SiC)	Silty clay loam (SiCL)	Sandy clay loam (SCL)	Clay (C)	Clay loam (CL)
Soil classified (FAO, 1998)	Vertic Cambisol	Haplic Calcaric Cambisol	Eutric Cambisol	Vertic Cambisol	Eutric Cambisol