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Tractor traction performance simulation on differently textured soils and validation: A basic study to make traction and energy requirements accessible to the practice

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ABSTRACT

Several models exist to simulate traction performance of a tractor, however, for most of them a proper experimental validation is missing. Moreover, their possible application for a practical use in a wide range of vehicles, equipment and soil configurations has never been further developed. This study examines a semi-empirical model of soil-tyre interaction, adapted to simulate the traction performance of mechanical front wheel drive tractors, taking into account not only mechanical soil and tyre parameters and static vehicle load but also the multi-pass effect, the load transfer effect, and the theoretical speed ratio between front and rear axles. This model simulates drawbar pull, traction coefficient, traction efficiency, and motion resistance as a function of slip, wheel load, tyre size and pressure. Several traction tests were performed on four Swiss agricultural soils of different type (clay, clay loam, silty loam, and loamy sand) in order to validate the model experimentally. Three tractors of widely ranging power (from 40 to 132 kW) and weight (from 24 to 68 kN) were used. Tractor configurations were varied by changing tyre pressure and tractor weight. Slip normally ranged between 5 and 30%. In most of the cases the model simulated drawbar pull as well as its variations due to changes in tyre pressure, wheel load, and soil strength reliably for practical purposes. Only when high wheel load was combined with low inflation pressure the model did not give suitable results due to an overestimation of the rolling radius. Based on the presented model, a convenient Excel-application called TASCV3.0 was developed for the practice. Such a practical computer-tool supports farmers in decision making concerning the tractor configuration, oriented to save fuel during agricultural operations.

1. Introduction

The traction performance of a tractor depends on several parameters related to the vehicle, its equipment, and the soil properties. Some of the vehicle parameters, such as the tyre inflation pressure and the wheel load, can be easily managed, therefore, enabling an optimisation of the work efficiency with a consequent reduction in fuel consumption and greenhouse gas emissions due to lower wheel slip, limitation of wear of the tyre tread, and reduction in the time required for tillage operations (Battiato and Diserens, 2013; Damanauskas et al., 2015; Damanauskas and Janulevičius, 2015; Dyer and Desjardins, 2003; Pichlmaier, 2012; Serrano et al., 2009).

Several models which simulate the traction performance of a tractor have been reported. Among these, the semi-empirical models represent a physical-based approach, which considers the mechanics of wheel-soil interaction, suitable for practical applications. Most of these models analyse the wheel-soil interaction considering a single wheel rather than a system of wheels, like in multi wheel drive vehicles. Experimental data to study the single wheel-soil interaction were often obtained by means of traction tests with a single wheel tester in a soil bin (Onafeko and Reece, 1967; Burt et al., 1979; Muro, 1993; Gharibkhani et al., 2012) or on-field (Upadhyaya et al., 1989, 1997; Shmulevich and Osetinsky, 2003), and in this latter case, the single wheel tester was usually connected to a tractor.

For a multi wheel drive vehicle, like a mechanical front wheel drive (MFWD) tractor, the multi-pass effect (Muro, 1997), the load transfer effect from the front axle to the rear axle, and the

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relationship between the slip of the front and rear wheels when the tractor moves with locked differential must be considered.

The adaptation of a single wheel-soil model to a multi wheel drive system can be used to simulate the traction performance of a tractor-soil system. This results in a variety of practical and valuable applications such as the selection of the best tractor configuration and the definition of the optimal range of slip, as a function of the soil characteristics and conditions, in order to optimise the traction performance in tillage operations.

The traction performance of agricultural tractors can be measured by means of field tests with full-scale instrumented tractors. Examples of results of field traction tests were reported by Zoz (1970), Zoz (1997), Shell et al. (1997), Turner et al. (1997), Zoz and Grisso (2003), Arvidsson et al. (2011), Diserens and Battiato (2012), Molari et al. (2012), Roşca et al. (2014), and Simikić et al. (2014) both for tractors with tyres and for tractors with tracks.

Among the semi-empirical tyre-soil interaction models presented recently, the model introduced by Shmulevich and Osetinsky (2003) has shown a high agreement with results reported in literature (Pope, 1969; Shmulevich, 1975; Gee-Clough, 1976; Muro, 1993; Du Plessis and Venter, 1993; Thangavadivelu et al., 1994) and experimental data obtained with a single wheel tester on concrete, on sand, and on a tilled soil. This model considers the load transfer effect affecting a drive wheel in a multi wheel drive vehicle and, therefore, offers the opportunity to be adapted in order to develop a comprehensive tool for predicting off-road vehicle performance.

In spite of the successful qualitative validation reported by Shmulevich and Osetinsky (2003), a need for further verification with data from experimental conditions different from those considered by these authors, was recognised (Osetinsky and Shmulevich, 2004). Furthermore, the possible application of this model to simulate the traction performance of multi wheel drive vehicles like MFWD tractors, which are very widespread in Europe, is of high interest for practical applications and therefore needs to be studied.

In this study, the traction performance is described in terms of drawbar pull *DP*, defined as the pulling force available at the tractor drawbar; traction coefficient μ_{tr}, defined as the drawbar pull *DP* to tractor weight $W_{tractor}$ ratio; traction efficiency η_{tr}, representing the fraction of power delivered to the tractor wheels that is available as drawbar power; and motion resistance due to soil compaction *MR*, corresponding to the vertical work performed by the wheels in making ruts of a defined depth after considering specifically the multi-pass effect, the load transfer effect, and the theoretical speed ratio between front and rear axles.

In a previous study (Battiato and Diserens, 2013), the influence of the wheel load and the tyre inflation pressure on the traction performance of an MFWD tractor of 65 kW on a cohesive soil was analysed on the basis of experimental measurements and simulations with an improved tractor-soil interaction model based on the approach to tyre-soil interaction proposed by Shmulevich and Osetinsky (2003).

With this present work, we aimed (i) to simulate the traction performance of three differently equipped MFWD tractors of power ranging between 40 and 132 kW in terms of *DP*, μ_{tr}, η_{tr}, and *MR*, as a function of the slip, the tyre pressure, and the wheel load and (ii) to substantiate experimentally the simulations of *DP* on the basis of traction tests under different tractor configurations in four Swiss agricultural soils presenting types from clay to loamy sand. The validated approach to model the traction performance of MFWD tractors was used as framework for developing a new computerized module for predicting traction and energy requirements analogously to *Terranimo* (Stettler et al., 2010, 2014) or *TASCV2.0* (Diserens et al., 2010), two tools concerning subsoil compaction risk for the practice.

2. Materials and methods

2.1. Field tests

2.1.1. Soil locations and properties

The traction tests were carried out at four sites, three in north-eastern Switzerland (one in Frauenfeld and two in Tänikon, region Winterthur) and respectively one in north-west Switzerland (Witzwil, region Neuchatel). The four sites had different soil textures and conditions: a field with clay soil and maize stubble in Tänikon, Ettenhausen (47°28′52″N, 8°54′14″E), a clay loam field with wheat stubble in Tänikon (47°29′0″N, 8°54′44″E), a silty loam field with maize stubble in Frauenfeld (47°34′32″N, 8°52′20″E), and a loamy sand field with maize stubble in Witzwil (46°59′30″N, 7°03′24″E).

At the considered stubble covered sites, the spatial variability of the penetration resistance, expressed in form of coefficient of

Table 1
Physical and mechanical parameters of topsoil in the four locations considered.

Soil property 0–0.10 m depth	C*	CL	SL	LS
Site	Tänikon	Tänikon	Frauenfeld	Witzwil
Latitude	47°28′52″N	47°29′0″N	47°34′32″N	46°59′30″N
Longitude	8°54′14″E	8°54′44″E	8°52′20″E	7°03′24″E
Sand [%]	20	31	20	86
Silt [%]	32	34	53	8
Clay [%]	48	35	27	6
Texture (USDA classification)	clay	clay loam	silty loam	loamy sand
Plant cover	maize stubble	wheat stubble	maize stubble	maize stubble
Volumetric water content θ [%]	27.0	28.4	40.2	15.2
Matric suction s [kPa]	6.11	9.45	1.27	57.40
Cohesive modulus of deformation (front) $K_{c,f}$ [kN/m$^{(n+1)}$]	2354.1	4554.8	298.2	1208.2
Frictional modulus of deformation (front) $K_{\varphi,f}$ [kN/m$^{(n+2)}$]	−4130.0	−3036.5	479.0	−805.5
Exponent of deformation (front) n_f	1.01	0.90	0.77	0.81
Cohesive modulus of deformation (rear) $K_{c,r}$ [kN/m$^{(n+1)}$]	2168.9	4554.8	298.2	1208.2
Frictional modulus of deformation (rear) $K_{\varphi,r}$ [kN/m$^{(n+2)}$]	−3498.3	−3036.5	479.0	−805.5
Exponent of deformation (rear) n_r	0.79	0.90	0.77	0.81
Cohesion c [kPa]	24.4	5.0	15.9	29.2
Angle of shear resistance φ [°]	18.0	30.0	25.6	6.4
Shear deformation modulus k [m]	0.014	0.010	0.010	0.012

* C = Clay; CL = Clay loam; SL = Silty loam; LS = Loamy sand.