Performance of wheel and track running gear on liquid manure spreaders

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McBride, R.A., McLaughlin, N.B. and D.W. Veenhof. 2000. **Performance of wheel and track running gear on liquid manure spreaders**. Can. Agric. Eng. **42**:019-025. A field experiment was conducted to characterize soil-vehicle interactions and to measure tractor power/fuel requirements when hauling a fully loaded tank spreader (18 m^3) fitted with rubber tracks (2721x635), high flotation tires (28L26) or conventional truck tires (445/65R22.5). A second objective was to apply an existing soil compaction model to the data from this field trial and to determine if its estimates of wheel rut depth were reasonable. The experiment was carried out in late autumn on a harvested soybean field (silt loam soil) located in southwestern Ontario. Fuel consumption and drawbar draft were measured during the traffic treatments with an instrumented tractor, and selected soil properties were measured afterwards. An analytical-type soil compaction model was used to estimate the wheel rut depth for the two pneumatic tire treatments. The type of running gear had a highly significant effect on both drawbar draft and fuel consumption ($p < 0.001$), with the tracks having the highest values (mean 24.6 kN and 21.5 L/h, respectively) and the flotation tires having the lowest (mean 13.9 kN and 16.9 L/h, respectively). The truck tires left ruts with a mean depth of 42.3 mm, while the flotation tires left cleat impressions that were barely discernable. A pedotransfer function was used to estimate the preconsolidation stress (26 kPa) and compression index (0.173) of the plow layer soil and, with these and other input data, the soil compaction model estimated rut depths that were quite comparable to those observed. The only ruts produced by the tracks were those of the track grousers (about 48 mm deep), but extensive soil shearing was evident. The tracks and truck tires produced significantly higher ($p < 0.05$) measured dry bulk densities at a depth of 150 mm when compared to those induced by the flotation tires. Soil cone penetrometer measurements were not as conclusive in distinguishing the impact of the running gear treatments on soil structural conditions. In general, however, flotation tires appeared to be the preferred running gear option with respect to several key parameters (fuel consumption, drawbar draft, wheel rut depth, dry bulk density) under these particular soil and loading conditions. **Keywords**: high axle load traffic, soil-vehicle interactions, wheel rutting, soil compaction model, pedotransfer function.

Une expérience en champs a été effectué pour évaluer les interactions sol-véhicule et mesurer les exigences puissance/carburant du tracteur lorsque tirant un épandeur plein (18 m^3) et équipé de chenilles (2721x635), de pneus à grande flottation (28L26) ou de pneus de camion (445/65R22.5). Un deuxième objectif visait à employer un modèle existant de compaction du sol en utilisant les données des tests au champs, et de determiner sa capacité prédictive (profondeur de l'ornière). L'expérience a été menée en fin d'automne dans un champs de soya déjà récolté (loam limoneux) au sud-ouest de l'Ontario. La consommation en carburant et l'effort de traction ont été mesurés durant les déplacements avec un tracteur spécialement équipé, et certaines propriétés du sol ont été mesuré par la suite. Un modèle analytique de compaction du sol a été utilisé pour estimer la profondeur des ornières des deux types de pneumatiques. Le système mécanique de transport a eu un effet significatif sur l'effort de traction et sur la consommation en carburant (p<0,001), les chenilles ayant les plus hautes valeurs (moyennes de 24,6 kN et 21,5 L/h, respectivement) et les pneus de grande flottation les plus faibles (moyennes de 13,9 kN et 16.9 L/h, respectivement). Les pneus de camions ont laissé une profondeur moyenne d'ornières de 42,3 mm, pendant que les pneus de flottation ont laissé des traces difficilement perceptibles. Une fonction de pédotransfert fut utilisée pour estimer la contrainte de préconsolidation (26 kPa) et l'index de compression (0,173) pour la couche arable, qui, combinées à d'autres données dans un modèle de compaction du sol, ont estimé des profondeurs d'ornières comparables à celles observées. Les seules traces produites par les chenilles étaient celles des parties en relief (approximativement 48 mm de profond), mais un important cisaillement du sol était observé. Les chenilles et les pneus de camion ont produit une mesure de densité apparente à une profondeur de 150 mm significativement plus haute (p<0,05) que les pneus de flottation. Les mesures de la résistance à la pénétration du sol se sont révélées incapable de distinguer les impacts des traitements sur la structure du sol. Généralement, les pneus à grande flottation ont été l'option préférée en ce qui concerne plusieurs facteurs importants (consommation en carburant, effort de traction, ornières de roue, densité apparente) sous ces conditions de sol et de trafic. **Mots-clés**: transport à charge lourde, interactions sol-véhicule, ornières de roue, modèle de compaction du sol, fonction de pédotransfert.

INTRODUCTION

The rapid expansion of intensive livestock production in Ontario, coupled with the preference for liquid manure management systems (e.g., tank spreaders) in the province, have created concern about excessive soil compaction and soil structural damage, given the large volumes of liquid animal waste that must be spread on agricultural land. For liquid manure, the tank spreader is the most common application method used in Ontario (Fleming 1985; Stonehouse et al. 1997), although lighter umbilical hose injection systems have been shown to require less power and fuel and to cause less soil and crop damage (Godwin et al. 1990). The size and capacity of hauled liquid manure spreaders have undergone significant increases in recent years (e.g., weight of up to 200 kN or more when fully loaded) and vehicles with tanks mounted on truck

The use of trade names is for convenience and does not constitute endorsement by the authors or the institutions they represent.

Fig. 1. Instrumented tractor towing an 18 m^3 liquid manure spreader (weight of 235 kN when fully loaded) equipped with rubber track running gear.

chassis can weigh as much as 400 kN. The very high ground pressures produced by these vehicles can lead to significant subsoil compaction and a corresponding reduction in crop growth and yield (Culley and Patni 1987; Håkansson et al. 1987). With some long growing season crops such as corn, farmers must often apply manure to fields either in early spring or late fall when the soil is relatively wet and more susceptible to compaction and other forms of structural degradation (e.g., plastic deformation or shear failure).

Farm producers in Ontario need a comprehensive decision support system (DSS) for manure management, which includes provision for the selection of the land application method from among the various options available. One method of reducing the soil compaction risk from high axle load spreaders is to lower the ground pressure with the use of high flotation tires. Flotation tires are generally more expensive than conventional tires, thus their benefits must be demonstrated to farmers before they are likely to invest in this optional equipment. The use of rubber track running gear can lower ground pressures even further due to higher contact areas than even large flotation tires. A disadvantage of passive track machines, however, is the amount of track skidding that usually occurs when turning (Erbach 1994). Additional lateral force must be exerted by the tractive device, and the track skidding can damage the surface soil (shear), particularly under wet soil conditions (Fig. 1). Furthermore, rubber tracks on powered vehicles are known to have a higher rolling resistance compared to pneumatic tires (Okello et al. 1994), due in part to deformation of the track on soil surfaces (Inaba et al. 1997). This higher power requirement might increase the size of tractor needed for efficient land application of liquid manure. Clearly, more research is needed on running gear/soil interactions (Voorhees 1993; Erbach 1994).

A field experiment was conducted where the main objective was to characterize soil-vehicle interactions and to measure tractor power/fuel requirements when an instrumented tractor pulled a fully loaded liquid manure spreader fitted with different running gear (rubber tracks, high flotation tires, or conventional truck tires). A second objective was to apply an existing soil compaction model to the data from this field trial and to determine if its estimates of wheel rut depth were reasonable. With additional validation, the intent is for this model to eventually become part of a comprehensive DSS for manure management in Ontario.

Fig. 2. Same spreader as for Fig. 1 but with conventional truck tires on the undercarriage.

Table I. Mean draft (on field soil and paved surface) and tractor fuel consumption when hauling a water-filled 18 m^3 liquid manure spreader equipped with different running gear.

Surface	Running gear					
	2721x635 (Rubber tracks)		445/65R22.5 (Truck tires)*		28L26 (Flotation tires)*	
	Mean	S.D.**	Mean	S.D.	Mean	S.D.
	Drawbar draft (kN)					
Soybean residue	24.6a***	0.7	19.4b	1.0	13.9c	1.7
Asphalt road	12.1a	0.4	4.1c	0.4	6.0b	0.4
	Fuel consumption (L/h)					
Soybean residue	21.5a	0.5	19.4b	0.7	16.9c	1.1

* tandem axle

** S.D. - Standard deviation

*** Means in the same row that are followed by different lower case letters are significantly different ($p < 0.001$) according to Duncan's multiple range test.

MATERIALS and METHODS

Field trafficking trials

The field experiment was carried out in late October on a harvested soybean field at the Elora Research Station (Elora, ON). The medium-textured soil belonged to the imperfectly drained London soil series (Hoffman et al. 1963) and the field had been under a conventional tillage system for some time. The Ap horizon was silt loam in texture (20% kg/kg clay, 55% kg/kg silt) with an organic carbon content of 2.0% kg/kg. An 18 m^3 liquid manure spreader (Husky Farm Equipment, Alma, ON) was used for the traffic trials. It was hauled by the instrumented research tractor of Agriculture and Agri-Food Canada in Ottawa (McLaughlin et al. 1993). The undercarriage for this spreader could be changed in about one half hour with a suitable overhead hoist. Three undercarriages with different running gear were used (Table I): i) conventional truck tires (445/65R22.5 @ 560 kPa) on a tandem axle (Fig. 2); ii) high flotation tires (28L26 @ 238 kPa) on a tandem axle; iii) rubber tracks (Fig. 1 - 2721 mm wheel base; two end wheels and four intermediate bogie wheels; 635 mm wide belt; 63.5 mm tractor tread-type grousers) (Model VFS50, Caterpillar Inc., Peoria, IL).

A factorial experimental design was used, with two tractor drive configurations (two wheel drive [2WD], and front wheel assist [FWA]), four running gear configurations (rubber tracks, flotation tires, truck tires, and tractor only [no spreader]) and three replicates (randomized complete block design). The two tractor drive configurations were included to determine possible fuel consumption differences. The tractor tire ruts (spaced 2080 mm centre to centre) were positioned well inside those of the ruts left by the spreader running gear (e.g., spaced 3210 mm for flotation tires, and 2690 mm for rubber tracks).

Plots were 20 m long and 10 m wide and the spreader was hauled through the plots at normal operating speed (about 6 km/h). The spreader was filled with water to simulate the weight of a full load of liquid manure. The total spreader weight when fully loaded was approximately 235 kN with a hitch weight of about 22 kN.

Drawbar draft and fuel consumption measurements were made with the instrumented tractor. This tractor was fitted with a set of transducers and an on-board data logger to measure and record tractor operating parameters such as drawbar draft, axle torque, fuel consumption, and engine, wheel, and ground speed. The tractor was brought up to speed in the buffer zone outside of the treatment blocks and a constant speed was maintained through the plots. Signals from all transducers on the tractor were logged at a scan rate of 100 Hz and low pass filters for strain gauge-based transducers on hitch instrumentation were set at a 10 Hz corner frequency. The spreader was periodically unhitched from the tractor and "zero files" were logged with no load on the tractor hitch. Means from these zero files were subtracted from the means from the treatment files to compensate for any instrument drift. Draft measurements were also made on a nearby asphalt road surface for comparative purposes (2WD only).

Mean values from each transducer were calculated for each plot and these means were considered as dependent variables in an analysis of variance (ANOVA) (SAS Institute 1996). Drawbar draft data for the 2WD and FWA field trials were pooled in the ANOVA since draft is a spreader parameter and would be unaffected by the tractor drive configuration. The tractor only (no spreader) treatment was also omitted from the ANOVA on draft data since the zero draft for this trial would bias the analysis of the draft for the different running gear. The tractor drive configuration (2WD and FWA treatments), however, was treated as a factor in the ANOVA on fuel consumption data.

The initial (pre-traffic) soil conditions were characterized by measuring soil water content using time domain reflectometry (IRAMS Soil Moisture Analyser, Campbell Pacific Nuclear Corp., Martinez, CA) and by measuring soil strength using a shear vane (50 mm diameter x 100 mm long vane) and a smaller Torvane device (Slope Indicator Co., Seattle, WA). Selected soil measurements were taken in the centre of both ruts left by the spreader after the traffic trials were complete. These measurements were i) dry bulk density by the manual core method (three cores [47 mm i.d. x 50 mm high] taken at each of the 150 and 300 mm depths in each plot), ii) dry bulk density using a CPN Stratagauge from 0 to 600 mm in 50 mm depth increments (Model MC-S-24, Campbell Pacific Nuclear Corp., Martinez, CA), and iii) cone penetration resistance (10 profiles in each traffic lane) from 0 to 450 mm with a standard soil cone penetrometer (Model CP10, Agridry Rimik Pty. Ltd., Toowoomba, Australia). The recording cone penetrometer had a 800 mm shaft and a small cone (base area 129 mm^2) with a 30° apex angle. A maximum insertion speed of 2 m/min was used (ASAE 1993).

Soil compaction modeling

Many soil compaction models are currently available (O'Sullivan and Simota 1995). The better examples include

Table II. Input data used in the modified Jakobsen and Dexter (1989) soil compaction model (*WheelVB*) for the Ap horizon.

Vehicle parameters			
	Flotation tires	Conventional truck tires	
tire diameter (mm)	1500	1150	
tire width (mm)	710	460	
mean tire inflation pressure (kPa)	238	560	
total vehicle weight per tire (kN)	53	53	
Soil parameters for Ap horizon*			
Measured or known			
initial dry bulk density			1.40 Mg/m^3
initial gravimetric soil water content			25% kg/kg
time since previous farm operations in the spring			150 d
time between passes of two tires on a tandem axle			1 s
soil water content change between tire passes			0% kg/kg
Estimated			
slope of the soil compression line (expressed in density-*ln*stress coordinates)			0.06 Mg/m^3
intercept of the soil compression line (saturated soil conditions)			1.236 Mg/m^3
coefficient of the term used to change the intercept of the soil compression line with changing soil water content			0.80 Mg/m^3
coefficient of the term used to determine the additional increase in soil density as a result of repeated tire passes			0.023 Mg/m^3
coefficient of the term used to determine the soil cohesion when multiplied by the preconsolidation stress			0.3 (unitless)
angle of shearing resistance			35°
coefficient of the term describing the gradual transition from confined compression conditions to critical state conditions			0.160 Mg/m^3
concentration factor describing the transmission of pressure with depth in the soil			4.0 (unitless)
fraction of estimated soil compaction occurring as a result of a single tire pass (time dependency of compaction process)			0.5 (unitless)
age-hardening constant			1.0 (unitless)
time constant describing the age-hardening factor			3 d

*Soil parameters are defined and discussed in Jakobsen and Dexter (1989)

many of the elements necessary to simulate soil mechanical behaviour under a range of initial soil and loading conditions. The *Wheel* model (Fortran program) of Jakobsen and Dexter (1989) has been chosen as a likely candidate to become part of a manure management DSS for Ontario. Reasons include its consideration of i) critical state soil mechanics in the estimation of wheel rut depth, ii) age hardening effects on soil strength, and iii) the time dependency of the compaction process. The *Wheel* model is classified as an "analytical" type (O'Sullivan and Simota 1995), with stress propagation described by the idealized Boussinesq equations. Prior to this study, the model had been translated from Fortran to Visual Basic (*WheelVB*) and a graphical user interface was added. The *WheelVB* model was used in this study to estimate wheel rut depth and other soil-vehicle interactions for the two pneumatic tire treatments.

The modelling component of the study also involved an investigation of the usefulness of the "preconsolidation stress" in characterizing the pre- and post-traffic structural state of agricultural soils as well as their vulnerability to further loss of total porosity with wheel traffic from high axle load spreaders. In unsaturated agricultural soils, this variable is regarded as the stress above which soil deformation greatly increases, or above which elastic properties give way to dominantly plastic behaviour (Kirby and Blunden 1991). This variable has been found to be very useful in regional studies aimed at establishing maximum wheel loading levels for vehicles in order to avoid further compression of soils (particularly subsoils) in agricultural fields (McBride et al. 1997). A pedotransfer function (PTF) developed for southern Ontario soils (McBride and Joosse 1996) was used to estimate the preconsolidation stress and several other important mechanical properties of the soil (Table II).

RESULTS and DISCUSSION

On the day of the traffic trials, the Ap horizon (0 – 200 mm depth) had a measured cohesive strength of about 30 - 35 kPa (Torvane), a volumetric soil water content (θ) of about 35% m^3/m^3 (i.e., a degree of saturation of about 0.77) and a dry bulk density (ρ_b) of about 1.40 Mg/m^3. The subsoil immediately beneath the plow layer had very similar properties (texture, density, water content), but the organic carbon content was much lower at about 0.3% kg/kg.

The conventional truck tires left very well defined ruts (overall mean depth of 42.3 mm), while the flotation tires left very wide and shallow imprints whose dimensions (less than 25 mm deep) were much more difficult to discern and measure against the field microtopography. The ruts produced by the rubber tracks were caused mostly by the imprint of the track grousers (about 48 mm deep) and not by the track belt, but extensive soil shearing and deformation were evident.

Analysis of variance indicated that the running gear had a highly significant effect on drawbar draft and fuel consumption ($p < 0.001$), with the tracks causing the highest draft and fuel usage and the flotation tires causing the least (Table I). The fuel consumption data were pooled for the 2WD and FWA trials in

Table III. Statistical summary of dry bulk density data measured from 50 mm high cores sampled at depths of 150 and 300 mm below the original soil surface (n = 9).

150 mm depth		300 mm depth	
Traffic treatment	Measured dry bulk density* (Mg/m^3)	Traffic treatment	Measured dry bulk density* (Mg/m^3)
Truck tire (FWA)	1.464 a	Truck tire (2WD)	1.467 a
Truck tire (2WD)	1.444 ab	Truck tire (FWA)	1.452 ab
Rubber track (2WD)	1.436 ab	Rubber track (2WD)	1.442 ab
Rubber track (FWA)	1.430 abc	Rubber track (FWA)	1.441 ab
Untrafficked control	1.409 bcd	Flotation tire (FWA)	1.441 ab
Tractor only (no spreader)	1.393 cd	Untrafficked control	1.418 ab
Flotation tire (2WD)	1.384 d	Tractor only (no spreader)	1.417 ab
Flotation tire (FWA)	1.373 d	Flotation tire (2WD)	1.401 b

*Means in the same column that are followed by different lower case letters are significantly different ($p<0.05$) according to Duncan's multiple range test.

Table I, since it was determined that the tractor drive configuration was not a significant factor in the ANOVA. The significant difference in draft between the two pneumatic tire configurations was likely related to the contrasting rut depths observed for these treatments and the resulting effect on rolling resistance (Inaba et al. 1997). Measured drafts for the rubber track running gear were surprisingly high. It was observed during the traffic trials that the belt was undergoing appreciable deformation around the four midwheels. Afterwards, it was observed that the soil between the grouser indentations had been sheared in most cases from the underlying soil, which may have contributed to the increased draft in this treatment.

On the asphalt road surface, the ANOVA again showed that running gear had a highly significant effect on draft ($p < 0.0001$), but the ranking of the two pneumatic tire treatments was reversed when compared to the field (soil) surface. The truck tires had much higher inflation pressures than the flotation tires (Table II), apparently resulting in a lower rolling resistance on the pavement.

Using only basic soil information (i.e., soil clay and organic carbon contents, and initial ρ_b), the PTF estimated that the preconsolidation stress of the surface soil before the traffic trials was 26 kPa, and the compression index was 0.173. With these and other necessary input data (Table II), *WheelVB* estimated the wheel rut depths observed for the flotation and truck tire treatments reasonably well (23 and 45 mm, respectively). The pressure distribution profiles estimated by the model suggested that the vertical pressures within the Ap horizon (0 – 200 mm) for the flotation and truck tire treatments (two tire passes on a tandem axle) remained above 200 and 400 kPa, respectively.

In general, both the soil ρ_b (Table III) and penetration resistance data (Fig. 3) indicated that most of the soil strain and structural change caused by the spreader traffic was confined to the upper 150 to 200 mm of the soil profile (Ap horizon). Others have similarly found maximum predicted and observed soil strain near the soil surface in spreader traffic trials on both coarse- and fine-textured soils (Brown et al. 1992; Chi et al. 1993a, 1993b; Bédard et al. 1997), which was attributed to high subsoil strength arising from past soil management history. In this study, the relatively low estimated values of the preconsolidation stress (26 kPa) and the compression index (0.173) suggested that it was the inherently low compressibility of the medium-textured soil (probably compounded by age-hardening effects) more so than the prestress history that caused the majority of the soil strain to be concentrated in the Ap horizon. McBride and Joosse (1996) reported a mean estimated preconsolidation stress of 20 kPa for Ap horizons in a large region of southern Ontario.

The ρ_b values measured at a depth of 150 mm below the original soil surface (in the centre of the wheel ruts) were consistent with observed trends in rut depths and with modelled estimates. The tracks and truck tires produced significantly higher ($p < 0.05$) measured ρ_b at 150 mm when compared to the flotation tires and untrafficked controls (Table III). Very little of this treatment effect was evident at the 300 mm depth, however, with only the truck and flotation tire treatments (2WD tractor configuration only) being statistically distinguishable (Table III). Similarly, significant differences ($p < 0.05$) could only be detected in the ρ_b profile data measured with the Stratagauge at the 100 and 150 mm depths, with the truck tire treatment producing higher mean ρ_b values than the tractor only (no spreader) and untrafficked control treatments. It was concluded that ρ_b values from the neutron thermalization /gamma attenuation method were derived from soil volumes that were generally too large to discriminate the relatively thin soil layers most affected by the vehicle loads.

Overall, the cone penetration profiles showed that the mechanical resistance to root penetration remained below the agronomically-important threshold of 2.0 MPa (Letey 1985) for all traffic treatments (Fig. 3). An analysis of variance performed on the penetration resistance data, however, was not strongly conclusive and did not corroborate the observations made from the ρ_b and rut depth data in terms of running gear

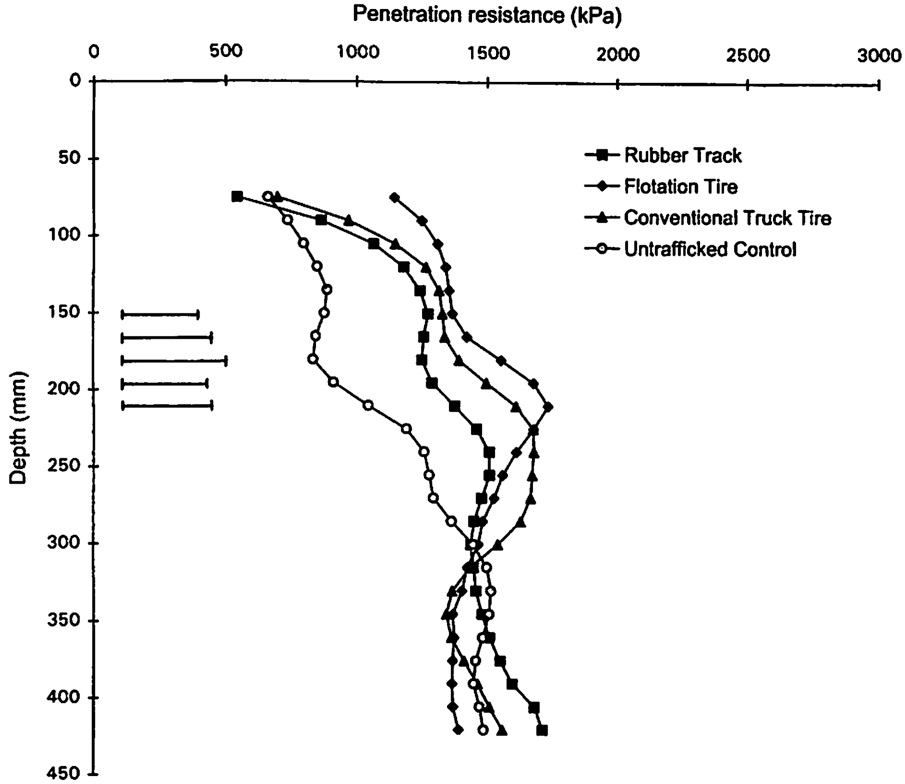

Fig. 3. Mean cone penetration resistance of soil vs depth for different running gear configurations in one of three experimental blocks (2WD and FWA data pooled). Bars represent $LSD_{.05}$ values calculated for those depths with significant F tests ($p < 0.05$).

effects. Mean penetration resistance measured beneath the ruts produced by the rubber tracks was significantly lower ($p < 0.05$) than that beneath the ruts produced by either pneumatic tire configuration, but only in the 150 to 210 mm depth range. There were no significant differences in this variable between the two tire types in this depth range or among any of the running gear configurations above or below this depth range. Examination of penetration resistance data from one experimental block in fact showed no statistical differences in this variable ($LSD_{.05}$) among any of the running gear configurations over the entire measurement depth (Fig. 3). A previous study that examined soil-vehicle interactions with powered vehicles equipped with different running gear and operating on very coarse-textured soils (Blunden et al. 1994) actually showed a significantly higher cone penetration resistance at 300 mm depth for tracks in relation to pneumatic tires. The difference in penetration resistance results between these two studies points to important distinctions in the stresses exerted on the soil by track/tire lugs of powered vs hauled vehicles, and their impact on soil structural conditions. The use of three-dimensional stress sensors in future studies of this type would help to clarify critical differences in stress distribution that can only be inferred from penetration resistance and other soil properties.

CONCLUSIONS

This study achieved its two stated objectives, and the following conclusions were drawn:

1. Drawbar draft measurements showed that the rolling resistance was significantly higher for the rubber tracks than for either of the pneumatic tire running gear (hard or soft surfaces). The surface firmness determined the relative ranking for the two pneumatic tire configurations, with a lower and higher rolling resistance for the truck tire on hard and soft surfaces, respectively, compared to flotation tires.
2. The observed depth of wheel rutting was not excessive (less than 50 mm) for any of the running gear configurations, despite the high estimated ground pressures and the late fall season (relatively high soil wetness). The high bearing capacity of the medium-textured topsoil was thought to be due to a combination of inherently low compressibility and age-hardening over the growing season. The relatively shallow rut depths and the concentration of most soil deformation (strain) in the Ap horizon did not produce strongly conclusive statistical contrasts in the soil physical property measurements taken on the different traffic lanes, but the flotation tires were generally shown to be the preferred running gear option (i.e., wheel rut depth, dry bulk density) under these particular soil and loading conditions.
3. The modified Jakobsen and Dexter (1989) soil compaction model, when supplied with a combination of measured and estimated soil property data, performed reasonably well in estimating wheel rut depth for two contrasting pneumatic tire configurations (i.e., different tire size and inflation pressure) in this single field trial. Additional validation efforts are warranted as part of the development of a DSS for manure management in Ontario.

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REFERENCES

ASAE. 1993. Standard S313.2 - Soil cone penetrometer. In *ASAE Standards 1993*, 657. St. Joseph, MI: ASAE.

Bédard, Y., S. Tessier, C. Laguë, Y. Chen and L. Chi. 1997. Soil compaction by manure spreaders equipped with standard and oversized tires and multiple axles. *Transactions of the ASAE* 40:37-43.

Blunden, B.G., R.A. McBride, H. Daniel and P.S. Blackwell. 1994. Compaction of an earthy sand by rubber tracked and tyred vehicles. *Australian Journal of Soil Research* 32:1095-1108.

Brown, H.J., R.M. Cruse, D.C. Erbach and S.W. Melvin. 1992. Tractive device effects on soil physical properties. *Soil & Tillage Research* 22:41-53.

Chi, L., S. Tessier and C. Laguë. 1993a. Finite element prediction of soil compaction induced by various running gears. *Transactions of the ASAE* 36:629-636.

Chi, L., S. Tessier and C. Laguë. 1993b. Finite element modeling of soil compaction by liquid manure spreaders. *Transactions of the ASAE* 36:637-644.

Culley, J.L.B. and N.K. Patni. 1987. Soil compaction from liquid manure tanker traffic. *Transactions of the ASAE* 30:1214-1218.

Erbach, D.C. 1994. Benefits of tracked vehicles in crop production. In *Soil Compaction in Crop Production*, eds. B.D. Soane and C. van Ouwerkerk, 501-520. London, England: Elsevier Science B.V.

Fleming, R. 1985. Liquid manure tank spreaders. OMAFRA Factsheet Agdex 743. Toronto, ON: Ontario Ministry of Agriculture, Food and Rural Affairs.

Godwin, R.J., N.L. Warner and M.J. Hann. 1990. Comparison of umbilical hose and conventional tanker-mounted slurry injection systems. *Agricultural Engineer.* p. 45-50.

Håkansson, I., W.B. Voorhees, P. Elonen, G.S.V. Raghavan, B. Lowery, A.L.M. van Wijk, K. Rasmussen and H. Riley. 1987. Effect of high axle-load traffic on subsoil compaction and crop yield in humid regions with annual freezing. *Soil & Tillage Research* 10:259-268.

Hoffman, D.W., B.C. Matthews and R.E. Wicklund. 1963. Soil survey of Wellington County, Ontario. Report No. 35 of the Ontario Soil Survey. Ottawa, ON: Research Branch, Canada Department of Agriculture.

Inaba, S., E. Inoue, T. Matsuo, K. Hashiguchi and S. Yamanaka. 1997. Travel resistance of the agricultural rubber crawler. I. Rolling resistance of track rollers. *Journal of the Japanese Society of Agricultural Machinery* 59:11-17.

Jakobsen, B.F. and A.R. Dexter. 1989. Prediction of soil compaction under pneumatic tyres. *Journal of Terramechanics* 26:107-119.

Kirby, J.M. and B.G. Blunden. 1991. Interaction of soil deformations, structure and permeability. *Australian Journal of Soil Research* 29:891-904.

Letey, J. 1985. Relationship between soil physical properties and crop production. *Advances in Soil Science* 1:277-294.

McBride, R.A. and P.J. Joosse. 1996. Overconsolidation in agricultural soils: II. Pedotransfer functions for estimating preconsolidation stress. *Soil Science Society of America Journal* 60:373-380.

McBride, R.A., G.C. Watson and G.J. Wall. 1997. Feasibility study on the development and testing of agri-environmental indicators of soil compaction risk (eastern Canada). Report No. 23 of the Agri-environmental Indicator Project. Report prepared for Agriculture and Agri-Food Canada, Research Branch, Ottawa, ON. October, 1997.

McLaughlin, N.B., L.C. Heslop, D.J. Buckley, G.R. St. Amour, B.A. Compton, A.M. Jones and P. Van Bodegom. 1993. A general purpose tractor instrumentation and data logging system. *Transactions of the ASAE* 36(2):265-273.

Okello, J.A., M.J. Dwyer and F.B. Cottrell. 1994. The tractive performance of rubber tracks and a tractor driving wheel tyre as influenced by design parameters. *Journal of Agricultural Engineering Research* 59:33-43.

O'Sullivan, M.F. and C. Simota. 1995. Modelling the environmental impacts of soil compaction: A review. *Soil & Tillage Research* 35:69-84.

SAS Institute. 1996. SAS user's guide: Statistics. Cary, NC: SAS Institute.

Stonehouse, D.P., Z. Islam and M.J. Goss. 1997. Sweet smell of success. *Ontario Milk Producer* 74(7):20-23.

Voorhees, W.B. 1993. Report of ISTRO Working Group B - Soil compaction by vehicles of high axle load. *Soil & Tillage Research* 26:252-253.