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Assessment of Dynamic Load Equations Through Drive Wheel Slip Measurement

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Abstract: Many parameters such as dynamic load of tractor drive wheels influence the traction of tractors. An increase in dynamic load of drive wheel increases the net traction, but excess dynamic load decreases the tractive efficiency that must be avoided. Development of tractor-mounted implements due to good maneuvering and weight transfer from front axle to rear axle led to effective performance of tractors. Therefore, sufficient knowledge regarding weight transfer phenomenon and dynamic load prediction or measurement is essential. Direct measurement of dynamic load on drive wheel encounters some problems and obstacles. An alternate approach to determine this important parameter is to use prediction equations of dynamic load. In this regard, a research effort was undertaken to choose the best equation. Four equations were considered; in equation 1 dynamic rear wheel load is assumed equal to tractor total static weight, in equation 2 the static rear wheel load and the amount of weight transfer is considered and equations 3 and 4 in which moment effect of front wheel rolling resistance in addition to static weight was taken into account. In this study, the equation given by ASAE Data 497.4 where wheel slip is calculated based on dynamic load was applied. Therefore, the calculated magnitudes were then compared to measured amounts through field tests. Results showed that equation 1 is the most fitting one and a relationship was obtained as the slip predicted by equation 1 is 0.915 of slip measured (R^2=.99, R.S.E= 0.55).

Key words: Dynamic load % Wheel slip % Weight transfer % Rolling resistance

INTRODUCTION

It is generally accepted that weight transfer plays an important role in safety and control of tractors and other ground vehicles. It has a direct effect on wheel sinkage and more importantly, on net drawbar pull. Furthermore, better performance of tractors in agricultural farms and exhibition of optimum traction depends upon the weight transfer and amount of dynamic load on drive wheels.

An increase in travelling speed, acceleration and traction force of a tractor or any automotive, causes a change in the amount of load on the front and rear axles. The main cause of weight transfer in an automotive is the change of acceleration or brake force. Whereas in the case of tractor, the tractive force exerted by implements also must be accounted. Regarding the constant travelling speed of tractor in most farm operations, usually the weight transfer resulted from implements is the main factor compared to other factors such as brake forces or acceleration changes.

Generally, the dynamic rear wheel load may be increased by (1) wheel weights, (2) tire ballast, (3) weight transfer from front wheels to the rear wheels and (4) weight transfer from implements.

In tractors, the traction ability of drive wheel is the product of normal reaction of soil to the wheel. Methods of implement hitching (drawn, mounted and semi mounted) change the amount of exerted forces on the tractor. If new machines are to make their most efficient contribution to agricultural product, it is important to be used effectively. Technical information on field performance of these machines is required for their efficient and effective use. This information can be provided to farmers through development of instrumentation systems for the machines involved in a field operation or through developed equations and computer simulation models. Either approach must be capable of providing this information in a form readily usable by farmers.

It is very difficult and costly to measure the relative importance of factors such as soil and tire interaction in a field operation because they can't be controlled. Developed equations are alternative methods of investigating the relative effect of various factors in a

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field operation by controlling other factors and studying the effect of an independent factor. In addition, simulation models of tractor performance are used on the basis of these equations [1].

In course of dynamic load measurement, Abbaspour [2] equipped a Mitsubishi tractor (MT-250D) to an instrumentation system. Since the diameter of the tractor's rear axle is large, therefore installation of strain gages on it gives a low sensitivity transducer. So, two extended axles with smaller diameter were bolted between the axle end and wheel by flanges. The strain gages were bonded on the extended axles and the dynamic load is measured through the output of Wheatstone bridge by a digital voltmeter [2].

In order to measure the field efficiency parameters, a tractor was instrumented by Clark and Adsit [3]. Strain gage transducers were employed to measure the front and rear axle loads. Calibrations for the transducers were accomplished by a platform digital scale under each wheels and the transducer's output was recorded versus different applied dead loads [3].

Burt *et al*. [4] studied the effects of dynamic load, soil type and soil compaction on the tangential to normal stress ratio on the soil-tire interface. In this study the ratio of unity was determined as the best ratio. The normal stresses on the soil-tire interface were measured by pressure transducers installed in the holes drilled on the tire lugs. Regarding to high costs of tires, this method is not recommended as a research method [4].

A tractor was equipped to an instrumentation package for measuring the performance parameters by **Mclaughin *et al*. (1993).** Parameters such as, front and real axle load, front and rear axle input torque, actual speed, slip and fuel consumption were measured in their study. A strain gaged sensitive pin was used to measure the front axle load. In order to record the resulting data, a PC-based data acquisition system was used [5].

Clark and Dahua [3] represented a model for weight transfer and traction of farm power units. To verify the model, an instrumentation system was developed and installed on the tractor. Each of the tractor wheels was supported by a hydraulic cylinder to measure the dynamic axle load [6].

Researchers in agricultural engineering have developed prediction equations for field machine operations [7-10] and mathematical modelling and computer simulations[11-15].

The objective of this study was to investigate the developed dynamic load equations and choose the best one through drive wheel slip measurements.

MATERIALS AND METHODS

1. Basic Equations: Four prediction equations for rear wheel dynamic load in this study were investigated as follows:

$$DWL_1 = TSWT \quad (1)$$

$$DWL_2 = SWL + DBP\left(\frac{DBH}{WB}\right) \quad (2)$$

$$DWL_3 = SWL + \left[\frac{TI - DBP(RRR - DBH) - RRFW(RRR)}{WB}\right] \quad (3)$$

$$DWL_4 = SWL + \left[\frac{TI - DBP(RRR - DBH) - RRFW(RRR - FRR)}{WB}\right] \quad (4)$$

Where:

DWL_1, DWL_2, DWL_3, DWL_4 are dynamic rear wheel loads as given by equations 1, 2, 3 and 4, respectively, N

TSWT = Total static weight of tractor, N
WB = Wheel base, m
TI = Torque input to rear axle, N.m
FRR = Rolling radius of front wheels, m
RRR = Rolling radius of rear wheels, m
DBP = Drawbar Pull, N
RRFW = Rolling resistance of front wheels, N
SWL = Static rear wheel load, N
DBH = Drawbar height, m

The last (or only) terms on the right-hand side of the equations 1, 2, 3 and 4 were taken from Colvin *et al*. [13], Bager *et al*. [16], Erwin [17] and Berlage and Buchele [18], respectively [13, 16-18]. In equation 1, the dynamic load of rear axle is assumed equal to total static weight of tractor. In such situation the front wheels are to rise up and all of the tractor weight is on the rear axle. Equation 2 is a very simple relationship that ignores torque input to rear axle and rolling resistance for all wheels and assumes constant velocity. Equation 3 is a more accurate prediction of dynamic wheel load because the torque input, rear-wheel rolling radius and front-wheel rolling resistance are considered. Equation 4 includes the front-wheel rolling radius in as much as the front-wheel rolling resistance is considered to act at the center of the front axle.

2. Slip Prediction: The predicted slip in decimal form is defined in the ASAE Standard D497.4 [19] as:

$$s = \frac{1}{0.3C_n} Ln\left(\frac{0.75}{0.75 - \left(\frac{NDBP}{DWL} + \frac{1.2}{C_n} + 0.079 \right)} \right) \quad (5)$$

where
s = Slip of drive wheel in decimal
C_n = Wheel numeric, dimensionless
DWL = Dynamic wheel load calculated by eqs, 1, 2, 3 or 4, N
$NDBP$ = Net drawbar pull, N

The wheel numeric (C_n) is defined as follows:

$$C_n = \frac{b \times d \times CI}{DWL} \quad (6)$$

Where; b is the tire width (mm), d is the tire diameter (mm) and CI is the cone index (MPa). The slip equation uses dynamic wheel load as an independent variable for slip prediction.

3. Rolling Radius: The rolling radius of a tire is defined in ASAE Standard S296.4 (2003) as the distance travelled/revolution (rolling circumference) of the wheel and tire divided by 2 [20]. The distance travelled per nine revolutions of the front wheel and five revolutions of rear wheel was measured three times. An average rolling radius was calculated as 0.407 m for the front wheel and 0.78 m for the rear wheel. In addition, the tire width was determined through the tire code as 467 mm.

4. Front-Wheel Rolling Resistance: Rolling resistance is defined in the ASAE Data D497.4 as the product of dynamic wheel load multiplied by the coefficient of rolling resistance, given as:

$$r_R = \frac{0.5}{C_n} + .04 \quad (7)$$

$$M_R = DWL \times r_R \quad (8)$$

Where; D_R is coefficient of rolling resistance and M_R is the rolling resistance force (N) and DWL is the dynamic wheel load. The following procedure was followed to determine the dynamic load of the front wheel. The tractor used in this study was weighed and the front-wheel axle weight was 14720 N and the rear wheel weight was

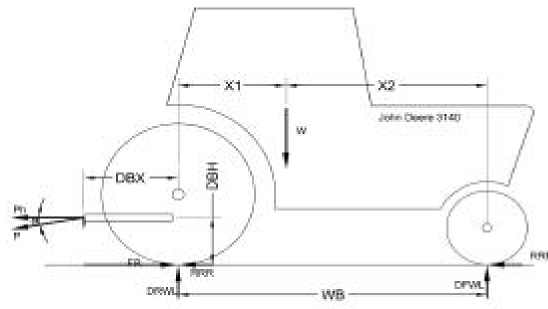

Fig. 1: Free body diagram of tractor under static loading

25010 N in static state. The draft angle (") was adjusted to be zero in duration of all the experiments. The free body diagram shown in Fig. 1 was used to determine the dynamic front-wheel load. Two assumptions were made; one was that soil reactions act at the center of the wheels below the axles. The second assumption was that tractor weight distribution on axles does not change with slope change below 5%. Summing moments about an axis through the rear wheel and soil surface contact, the front-wheel soil reaction or the dynamic front-wheel load (DFWL) is found as:

$$DFWL = \frac{W(X_1) - P_V(DBX) - P_h(DBH)}{WB} \quad (9)$$

Where; P_h is the horizontal component of pull, which was measured by a drawbar pull transducer, installed between the two tractors. Also, the amounts of DBH and WB were measured as 82 and 257 cm, respectively.

5. Cone Index Measurement: A digital hand-pushed penetrometer was used to measure the cone index for substituting in wheel numeric equation. In the penetrometer (Fig. 2), a cantilever beam strain gage load cell and a photodiode sensor measured the penetration force and penetration depth, respectively. A microcontroller-based data acquisition system recorded the cone index values. In this study the cone index was measured to a depth of 30 cm. The average of cone index in 10 replicates was determined as 2.795 MPa (0-30 cm). Three samples of soil in depths of 10, 20 and 30 cm were taken for moisture context measurement and soil texture determination. The moisture content of the soil was 10%. w.b. and the texture was clay-loam.

Fig. 2: Digital hand-pushed penetrometer

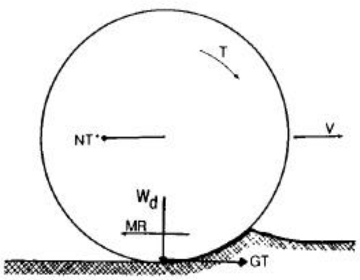

Fig. 3: Free body diagram of the drive wheel

6. Slip Measurement: Percentage of drive wheel slip in traction mode is defined in ASAE Standard S296.4 as:

$$s\% = [1 - \left(\frac{V_a}{V_t}\right)] \times 100 \quad (10)$$

Where; V_t is the theoretical speed or the speed without slip and V_a is the actual speed. For measuring the speeds, travelled distance and the time for 10 revolutions of rear wheel were measured. Also, on the concrete and without any tractive force, the actual speed of the tractor was measured in circumstances similar to the field experiments (engine speed and transmission position).

7. Input Torque of Drive Axle: According to the free body diagram of the drive wheel as shown in Fig. 3, if the net traction measured with load cell and rolling resistance value is summed up, the result is known as gross traction (GT). The input torque is obtained by multiplying the gross traction and rolling radius values, as given:

$$GT = NT + M_R \quad (11)$$

$$T = GT \times r \quad (12)$$

where NT is designated as net traction (N), M_R is the rolling resistance (N), r is the rolling radius (m) and T is the input torque (N.m).

For computation of the input torque using equation (11, 12), the rolling resistance values of the front and real wheels are required. The rolling resistance of the front wheel is obtained by Eqs 7, 8 and 9. Since the amount of rear wheel dynamic load is unknown, therefore an assumption was considered in such a way that rear wheel dynamic load merely for calculation of rolling resistance was determined by the method used for front wheel as follows:

$$DRWL = \frac{P_h(DBH) + W(X_2)}{WB} \quad (13)$$

8. Data Acquisition System: In order to record the load cell output, a data acquisition system comprising of a programmable data logger (Model, CR10X) with 8 differential voltage channels and 4 pulse channels along with an interface (SC32A) with RS-232 serial cable (Campbell, USA) and a laptop computer for processing and monitoring the data was used. The interface software PC208-W3.3 between transducer and data logger was also developed by Campbell, USA. The software was used to program the data logger. After running the software, the data logger is capable of receiving output signals from the load cell and signal values are shown as a text or dynamogram on the laptop and recorded on the memory.

9. Field Tests: Field tests were conducted in Experimental-Farm of University of Tehran, Karaj, Iran. A John Deere 3140 and a Mitsubishi (MT-250) along with a moldboard plow and a 2.2 KN load cell and the data acquisition system were used for the field tests. The John Deere tractor was used as a towing tractor and the other as a towed tractor.Tractive forces in 15 levels varying from 6.5 to 20.6 KN were applied to John Deere tractor by different depths of moldboard plowing along with manual braking of the rear tractor (Fig. 4). The slip value of John Deer tractor was measured by the method stated above with 5 replicates for any level of tractive force. The load cell data were saved in data acquisition system and analyzed after transferring to a laptop computer.

Fig. 4: Field tests for measurement of slip and tractive force

Using the measured parameters during the field tests, the values of dynamic rear load were calculated by four developed prediction equations. By substituting, these values in slip prediction equations predicted slip values were obtained. The measured and predicted slip values were analysed and compared in Excel-2007 spreed sheet and the best equation for dynamic load prediction was selected through linear regression analyses.

RESULTS AND DISCUSSIONS

Averages of measured slip in 15 levels of tractive forces with 5 replicates for each level are shown in Table 1. Since in the field tests, drive wheel slip was measured manually on one side of the tractor (left side), therefore in direct trajectories, differential lock of the tractor was engaged to reduce the measurement errors, especially in high levels of tractive force. In electronic slip measurement systems, a Doppler radar is used as an actual velocity sensor and a magnetic pickup for theoretical speed measurement (on front wheel or fifth wheel), therefore with these systems, the values of measured slip are reliable without application of differential lock.

Analysis of obtained data showed that prediction of slip with equation 1 had the greatest agreement with the measured slip. The other three equations for dynamic wheel load used in this study were close to each other as shown in Fig.5. Also, the results of linear regressions for four equations are shown in Table 2. The second terms of equations 2, 3 and 4 are weight transfer equations. The reliability of these equations was documented by Townsend and Domier [21]. They tested these equations against their measured weight transfer data and reported that equation 4 was the best estimation for weight transfer among the three equations used. However, their report

Table 1: Predicted and measured slip values in 15 levels of pull forces

		Slip (%)				
Test NO	Tractive Force (kN)	Measured	Predicted1	Predicted2	Predicted3	Predicted4
1	6.50	10.00	9.10	13.80	14.40	13.90
2	8.40	11.50	10.70	17.40	16.40	16.00
3	9.40	12.30	11.20	18.40	17.70	17.10
4	10.80	13.70	12.10	20.50	19.90	19.70
5	11.60	15.20	14.30	23.10	21.70	21.05
6	13.30	18.30	17.00	28.80	27.00	26.40
7	14.10	19.60	16.60	29.00	28.70	28.00
8	14.60	21.00	19.40	32.30	29.80	28.90
9	15.30	22.40	20.00	34.70	33.60	32.60
10	15.90	23.40	22.50	34.30	33.70	33.90
11	17.60	25.10	23.10	37.10	36.40	35.90
12	18.60	26.20	23.30	39.40	35.10	34.20
13	19.10	27.60	25.40	40.70	39.10	37.30
14	19.60	28.10	25.60	42.50	40.50	38.20
15	20.60	29.50	27.40	44.40	41.70	40.10

Table 2: Statistical information for slip comparison of four equations

Model	Regression Eqs	Std. Err. of Pred. Est.	R-Square
Equation 1	$S_p = 0.915\ S_m$	0.551	0.99
Equation 2	$S_p = 1.504\ S_m$	0.711	0.97
Equation 3	$S_p = 1.432\ S_m$	0.840	0.96
Equation 4	$S_p = 1.389\ S_m$	1.038	0.95

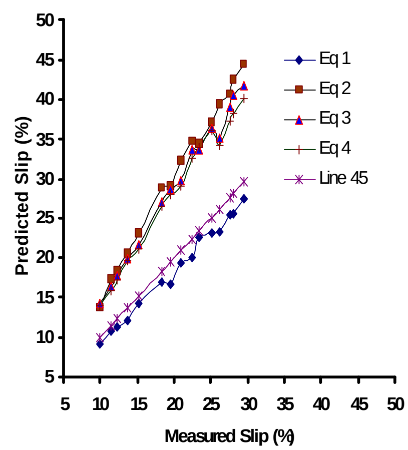

Fig. 5: Predicted and Measured slip presentation from equations

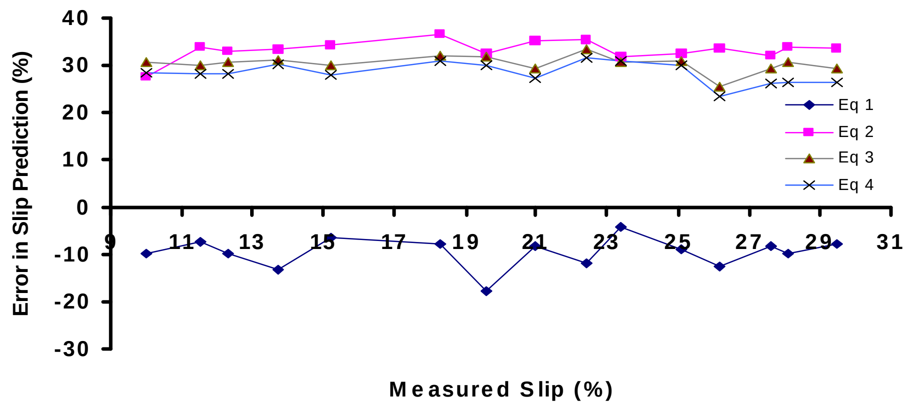

Fig. 6: Percent error involved in comparison of slip predicted from four equations

indicated a 9% to 20% error in predicting weight transfer from equation 4 and this was less than that of the other three equations. The equations 2, 3 and 4, had an over prediction compared to the measured values, but the equations 1 has an under predication as shown in Fig.5. In addition, the regression line of equation 1 is fairly close to the line of 45 degree. The amounts of regression equation standard error for these four equations were calculated and given in Table 2. Also, the values of error are shown in Fig. 6. It is clear that equation 1 has the least values of error. These findings are in agreement with those of Alimardani *et al*. (1987). They used these equations in a simulating software (TERMS) and Eq. 1 had the best verification with the software.

A relationship was found between the measured slip and predicted slip with this assumption that equation 1 is the best equation as $S_p = 0.915\ S_m$. As shown in Fig. 5, prediction values by equation 1 is less than those of measured slip as well as the slope of line is close to one (0.915).

CONCLUSION

In order to choose the best equation for prediction of rear axle dynamic load of 2WD tractors, experiments were conducted on the basis of drive wheel slip measurement. The measured and predicted slip values were compared by linear regression analysis and so the Colvin's equation (Eq. 1) was selected as the best dynamic load prediction equation. This word proved that the total static weight of the tractor is the best substitution for dynamic load of rear axle.

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