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CONTENTS

Performance evaluation of hydraulic normal loading device on varying soil conditions for indoor tyre test rig

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ABSTRACT: The radial-ply tyre (14.2R28) was tested to validate the performance of the hydraulic normal loading device at dynamic conditions. Tyre was tested at two different soil bed conditions at different drawbar pulls until the wheel indicate up to 15% slip. Drawbar pull was applied with the help of a drawbar loading device. Drawbar pull, slip and actual hydraulic normal load experience by the wheel were measured with transducer and recorded with the help of data acquisition system**.** Tractive efficiency and slip of the tyre were measured at different pulls and compared the same with dead load. The hydraulic normal loading system was used to study the effect of normal load on the tyre under soft and hard bed soil conditions. It was observed that with the hydraulic loading device, the normal load on the wheel axle under dynamic conditions was found to increase in the range of 1.18 to 5.1% for soft and1.9 to 4.1% hard bed soil surface. Average variation in tractive efficiency and slip was 1.43% and 1.03%, respectively for hard and 4.03% and 1.28%, respectively for soft soil at varying pull up to slip 15%. The effect of soil hardness was found to be significant ($p < 0.04$) on tractive efficiency and slip at 5% level.

Key words: Drawbar pull, hydraulic system, normal loading, radial-ply tire, slip

The prediction of tractor performance efficiency has been the ultimate goal for many traction investigators.The tractors efficiency can be improved by maximizing the fuel efficiency of the engine and drive train, maximizing the tractive advantage of the traction devices (tyres), and selecting an optimum travel speed for a given tractor-implement system. Research outcome shows that approximately 20-55%of useful tractor energy is lost at the tyre-soil contact surface. This energy isn't only misused but scuffs the tyre and compresses the soil to a grade that will be unfavourable to crop production (Bohnert and Kenady, 1975, Kumar *et al*., 2013). The traction of tyre depends on tyre geometry (section height, width, diameter), tyre nature (radial, bias), lug design, inflation pressure, normal load on axle and soil nature (Brixius, 1987). Generally, a tyre is tested in soil bin where the tyre is allowed to run at varying normal loads, pulls and soil hardness levels to investigate parameters like pull, slip, tractive efficiency and coefficient of traction. For most off-road applications, the terrain must deform significantly to produce the stresses required to support the vertical load imposed on the tyre. The tyre also deforms depending primarily on its inflation pressure, normal load and to a lesser extent on its carcass stiffness. A general rule of thumb is that; the average surface contact pressure is slightly higher than the tyres inflation pressure with the difference attributable to carcass stiffness. The mean contact pressure multiplied by the contact patch area must equal the applied vertical load. The mean contact pressure multiplied by the contact patch area must equal the applied vertical load (Kumar *et al.,* 2018). If the inflation pressure is increased at constant vertical load, the tyres soil interaction must decrease the area of contact patch. Or, if the inflation pressure is held constant, decrease in vertical load must also be accompanied by decrease in tyre deflection and contact patch area. Knight and Green (1962) conducted deflection tests on firm and various test surfaces at different speeds to measure vertical and or lateral deflections of moving tubeless tyres with the help of linear and circular potentiometers. This technique for measuring deflection was also used by Krick (1969) and Li *et al.* (1985). Results showed that the shape of the tyre appeared to be at least a crude indicator of the distribution of forces imparted by the tyre to the surface on which it was operating, as well as an indicator of its ability to travel on that surface. The tractive performance of tyre can be evaluated in single tyre testing soil bin laboratory. The soil bin laboratory should have provisions to measure parameters such as pull, actual velocity, torque, axle rpm, tyre sinkage and dynamic normal load on tyre (Taylor *et al.,*1976; Tiwari 2006).

Burt *et al.* (1979) investigated the role of both dynamic load and slip-on tractive performance. The results of this study demonstrated that large changes in performance were seen with small changes in slip. However, at higher slip, changes in dynamic load had a greater effect on performance than changes in slip. At constant slip, tractive efficiency increased with increases in dynamic load on compacted soil. On the soils with an uncompacted subsurface, tractive efficiency decreased with increase in dynamic load (Elwaleed *et al.,*2006). Wonderlich and

Goodall (2007) developed a dynamic loading device for single wheel testing unity. The loading system consists of a hydraulic cylinder and an adjustable pressure reducing/relieving valve. The force capable of being enveloped was 23.6 KN at 3000 psi (206 bar). The Agricultural and Food Engineering Department of IIT Kharagpur has an indoor soil testing facility to test the various sizes of tyres used in tractors. Tiwari (2006) conducted test and reported that the effect of normal load is highly significant on tractive performance. The combined effect of normal load and inflation pressure is also significant on tractive performance of tyres. The tractive efficiency of the tyres increased while wheel slip decreased with decrease in normal load. The increase in slip with increase in normal load for a constant coefficient of traction may be due to increase in pull in proportion to the dynamic weight. Tiwari (2006) measured the tyre deflection on the rigid surface for bias-ply tyres. The normal load was varied from 7.36 kN to 18.64 kN and inflation pressures from 69 kPa to 234 kPa. The test tyre is loaded by putting dead weights on a platform attached to the test wheel. This is a very laborious and strenuous exercise, particularly when heavy loads are required for testing large tyres (Kumar 2009; Kumar 2012; Kumar *et al.,* 2013; Kumar *et al.,* 2020a). Besides, the irregular placement of dead weights may affect smooth operation of the tyre on the bed. This operation may be facilitated by using a hydraulic loading device. To successfully manage the dynamic wheel loading, an appropriate hydraulic loading circuit was designed. The loading circuit represents the expected method of providing dynamic loading to the wheel. Flow-through the circuit is controlled by the spool valve on the tractor hydraulic system. The hydraulic cylinder is connected through a pressure reducing/relieving valve which keeps the loading constant over varying terrain conditions (Kumar *et al.,* 2018). It was reported that there was a sudden increase in pressure in cylinder due to sinkage to attain soil level by tyre (Kumar *et al.,* 2013; Kumar *et al.,* 2018). So a study on hydraulic normal loading was undertaken to find its effect on tractive performance of tyre on varying load and soil compaction. Such a device would help in testing not only the large tyres at higher loads but also the small tyres where reduced loads are required.Traction performance parameters of radial-ply tyres such as slip (s), tractive efficiency (TE) and hydraulic vertical normal load (HNL) were evaluated at varying soil and pull conditions.

MATERIALS AND METHODS

Design and development of hydraulic circuit for normal loading

The double-acting hydraulic cylinder was mounted in such a position that the piston rod is vertical to the plane of carriage and just above the axle of the tyre. Preferably it is fixed to the frame which is supported from the trolley behind the main carriage. A 4-port, 3 positions double direction control solenoid valve is used to extend or retract and thereby increase or decrease the load on the tyre from a remote distance. The selection of relief valve is primarily based on the maximum operating pressure of the system. Since the maximum pressure was 4 N/mm^2, therefore, a direct-acting relief valve of 0-5 N/mm^2 was selected. The reservoir has three drain lines, one suction line and another port for filling the hydraulic fluid. The size of the hose selected for this circuit is 6.35 mm inner diameter with maximum pressure bearing capacity of 22.5 N/mm^2, which is more than 5 times the maximum operating pressure. The detail of the designed and the selected hydraulic components is shown in Table 1.

Hydraulic loading circuit diagram for tyre test rig

The tractive performance of tyre was conducted at varying

Table 1: Selection of hydraulic components

Sl. No.	Component	Design values or requirements	Available in market
1	Pump	Type: gear Capacity: 7.5 x 10^{-5} m^3/s	Type: gear Capacity: 8.3 x 10^{-5} m^3/s
2	Cylinder	Type: Double- acting Cylinder diameter: 39.51mm Rod diameter: 19.75 mm Maximum Push: 4.9 kN Maximum Pull: 3.67kN	Type: double acting Cylinder diameter: 40 mm Rod diameter: 22 mm Maximum Push: 5 kN Maximum Pull: 3.75kN
3	Piston	Stroke speed: 60 mm/s Return stroke speed: 82.4 mm /s Pressure range: 0–4 N/mm^2	Stroke speed: 60 mm/s Return stroke speed: 89.6 mm/s Pressure range: 0–40 N/mm^2
4	Directional control valve	Type: four-port, three-position Control: solenoid operated Pressure rating: 31.5 N/mm^2	Type: four-port, three-position Control: solenoid operated Pressure rating: 31.5 N/mm^2
5	Pressure relief valve	Type: direct operated variable type Pressure rating: 0–5 N/mm^2	Type: direct operated variable Pressure rating: 0–5 N/mm^2
6	Reservoir capacity	0.015 m^3	0.015 m^3

vertical normal load. The application of various loads on test rig was done with help of hydraulic system. Load on hydraulic tyre axle can be easily increase and decrease with help of extend and retract mode of hydraulic cylinder and with the help of relief valve. A hydraulic circuit was designed and developed for application of vertical normal load on tyre axle.This hydraulic system was fabricated with help of various hydraulic components. It consisted of a 10 lpm size pressure relief valve, a double-acting hydraulic cylinder of diameter 40 mm, a solenoid operated direction control valve, a ring transducer, an external gear pump, a 2 hp electric motor and a hydraulic oil reservoir with an oil filter.A strain gauge mounted on ring transducer was fitted on the end of the piston cylinder to measure the load on tyre in real-time. The ring transducer reading was recorded in DAS system and real-time display on the computer.The developed hydraulic system was fitted over tyre test rig to apply hydraulic normal load on tyre for traction performance. Hydraulic loading circuit is shown in Fig.1.

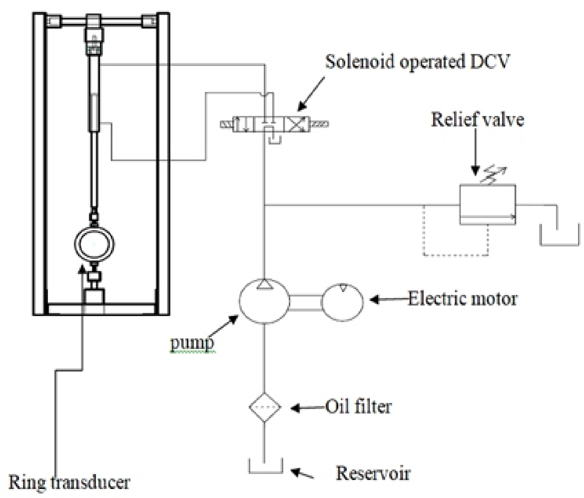

Fig.1: Hydraulic loading circuit on tyre test rig

Experimental setup

Tractive performance of tyre was conducted at soil bin traction laboratory at Agricultural and Food Engineering department of IIT Kharagpur. Traction laboratory has facility to test the different sizes of tyres at varying vertical load and pulls at different compaction levels of soil. The laboratory system consisted of a tyre test rig, an indoor soil bin, radial-ply tyre, a soil processing trolley, and a drawbar pull loading device. Tyre test rig was attached with different sensors to measure the real time data of tractive performance. Test rig consisted of a double-acting hydraulic cylinder to apply the vertical load with the help of hydraulic power system. Proximity sensors were used to measurement of slip with the help of recorded data of actual and theoretical speed (Tewari *et al.,* 2014; Chandel *et al.,* 2018; Tiwari *et al.,* 2019; Kumar *et al.,* 2020a).

1. Test ring, 2. Double acting hydraulic cylinder,3. Ring transducer, 4. Actual speed sensor 5. Hydraulic power system

Fig.2: Constructional details of the tyre test carriage with hydraulic system

A ring transducer was used to measurement of normal loading force and pull force. Axle power of the tyre was measured with the help of torque transducer and axle rpm sensor (Chethan *et al.,* 2018; Kumar *et al.,* 2020b). The tyre test carriage with hydraulic system is shown in Fig. 2.

Test procedure

Soil bed was prepared with the help of soil processing trolley and moisture level was maintained with the help of water sprinkler. The soil was leveled by leveler and compaction of soil was done with the help of hydraulic compaction roller. The soil hardness was measured with hydraulically operated cone penetrometer. Pull on the tyre was applied with the help of the braking drum. The vertical normal load was applied with the help of double-acting hydraulic cylinder and hydraulic power system. To investigate the effect of hydraulic normal loading (HNL) behavior on soft and hard soil condition, vertical normal load was applied on test tyre with help of hydraulic cylinder and pressure relief valve. The tyre was tested as per the research plan at different drawbar pulls until wheel indicate up to 15% slip range. Drawbar pull was applied with the help of drawbar loading device. Slip, drawbar pull and actual hydraulic normal load experience by the wheel were measured with the help of MGC plus data acquisition system (Hottinger Baldwin Messtechnik GMBH, Berlin, Germany) and real-time data were recorded**.** A program is written to execute parameters like average pull, normal load, actual and theoretical velocity. Real-time data was recorded in the DAS system and used to determine the coefficient of traction, slip and tractive efficiency, and angular velocity of the wheel (Kumar *et al.,* 2013). The final results appeared on a computer screen with a graphical display and during each experiment were saved in an excel file. The tyre test in the soil bin laboratory is shown in Fig. 3 and the research plan of evaluation is shown in Table 2.

Fig. 3: Tyre test on soil bin

RESULTS AND DISCUSSION

Comparative performance of a radial tyre using hydraulic load under varying soil conditions

A hydraulic normal load of 400 kg was set on wheel carriage by using the developed hydraulic circuit. The directional control valve was set in extending mode and the wheel was set in motion. The load dropped down considerably due to sinkage, but it was maintained after sometime. During the entire process of run, the load fluctuated because of tyre sinkage on the soil surface. The hardness of the soil bin bed was measured with the help of a hydraulic cone penetrometer up to sinkage depth before conducting the experiment. The average dynamic normal load was found to be slightly more than the normal load that was kept initially on the tyre. The sinkage of the bed was also measured of 70 mm. The normal loading behaviour of the tyre with drawbar pull is presented for soft bed (Fig. 4) and for hard bed (Fig. 5). In the case of soft bed variation in increase in load w.r.t static load was found to be in the range of 1.18 to 5.1% and its corresponding average increase in hydraulic load was 404 to 420 kg at different pulls. An increase in load w.r.t static load was found to be in the range of 1.9 to 4.1% and its corresponding average increase in hydraulic load was 407 to 418 kg at different pulls. There was no significant difference found between dynamic vertical load and initial load apply at 5% level of significance. The variation in load may be due to increase in thrust load and rolling resistance force as increase in pull and soil hardness.

Table 2: Research plan

Independent parameters:	
1. Tyre:	14.9R28
2. Inflation pressure:	14.8 psi
3. Normal load:	1150 kg (750 kg tyre test rig +400 kg hydraulic weight)
4. Drawbar pull:	Increasing pull till wheel indicates 15% slip
5. Soil compaction level:	(i) 600 to 700 kPa for soft soil (ii) 1700 to 1800 kPa for hard bed

Replications- 3

Dependent parameters:

1. Wheel slip, %
2. Tractive efficiency (TE), %
3. Dynamic normal load, kg

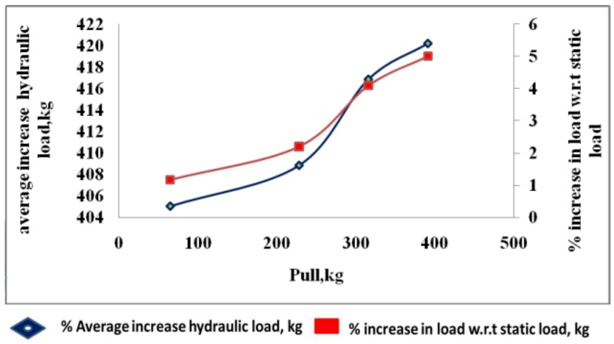

Fig. 4: Effect of pull on hydraulic normal load during dynamic condition on soft bed soil

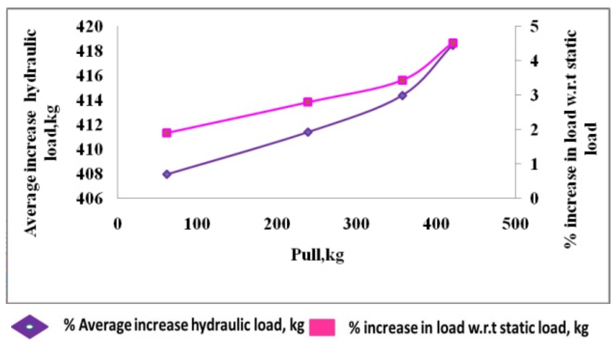

Fig. 5: Effect of pull on hydraulic normal load during dynamic condition on hard bed

Comparative performances of slip and tractive efficiency (TE) for radial-ply tyre at 1150kg hydraulic and dead weight loading on soft and hard bed are shown in Fig.6 and Fig.7. An appropriate statistical analysis was selected for analysis of variance using the statistical software package. All the variables under study significantly($p< 0.05$) affected to TE and slip. It was found that TE for hydraulic normal loading was less than dead weight loading on hard bed, it may due to rolling resistance and variation in soil bed, but there is no remarkable difference on soft bed condition. It was observed that in the case of hard soil maximum difference in TE and slip was 2.57% and 1.10% respectively, as compared to observation obtained from that of static load. In the case of soft bed conditions, tractive efficiency and slip were 7.43% and 2.52%, respectively. Average TE and slip variation was 1.43% & 1.03%, respectively for hard and 4.03% & 1.28%, respectively for soft soil at varying pull up to slip 15%.

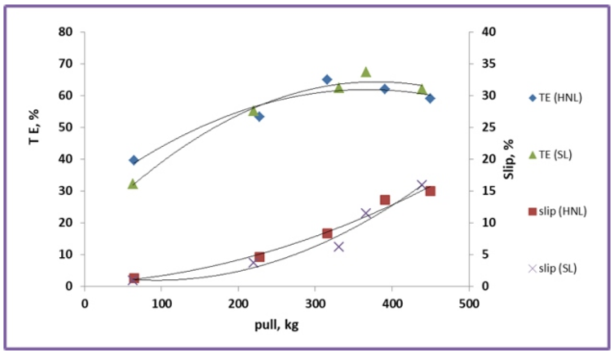

Fig. 6: Comparative performance of slip and TE for radial ply tyre at 1150 kg hydraulic and dead loading on soft surface.

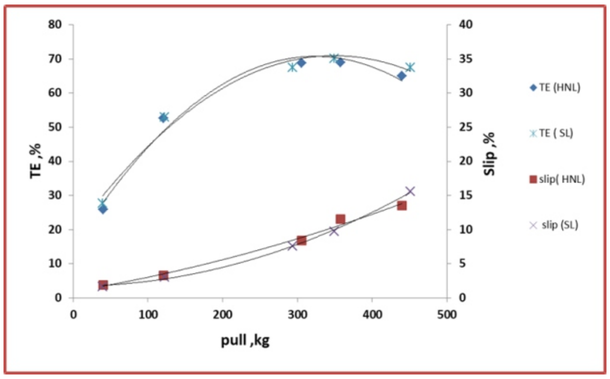

Fig. 7: Comparative performance of slip and TE for radial-ply tyre at 1150 kg hydraulic and dead loading on hard surface

CONCLUSION

An efficient hydraulic normal loading device was developed and evaluated, which could save time and labour and reduce the drudgery of experimenter. It was observed that developed hydraulic circuit is able to increase and decrease the load at wheel axle with the help of a directional control valve and pressure relief valve. The variation in hydraulic normal load was found to be 1.18 to 5.1% for soft bed and 1.9 to 4.1% for hard soil bed compare to static load condition, respectively. It was found that tractive efficiency and slip were significantly dependent on pulls ($p < 0.05$) and varying soil conditions up to slip 15%.The maximum difference in TE and slip was 2.57% and 1.10% respectively, as compared to observation obtained from that of static load.

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