Design and development of vertical loading mechanism for indoor agricultural single tyre test carriage

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ABSTRACT: The present study was undertaken to upgrade the existing traction laboratory of Agricultural and Food Engineering Department of IIT Kharagpur for the reduction in drudgery and easy operation. A vertical loading mechanism using hydraulics was designed to apply additional normal load up to 25 kN on wheel axle and remove 13 kN load from the initial load. The circuit used for applying force consisted of a fixed displacement pump, a 3-way, 4-port directional control valve, a relief valve and a double-acting cylinder. Load transducer based on proving ring for 40 kN load bearing capacity was developed. The ring was calibrated to get a relationship of voltage and load. The calibration was taken both tensile and compression modes. Vertical loading mechanism by hydraulic was validated in both static and dynamic conditions. Validation of hydraulic normal loading was done with test tyres under static and dynamic conditions. The vertical load was varied from 7.85 kN to 10.30 kN using a hydraulic loading mechanism under both static and dynamic conditions. A bias-ply tyre and a radial-ply tyre, each of 13.6x28 sizes were selected under this study in soft soil conditions. The soil cone index was maintained between 0.6 to 0.8 N/mm^2. Under the static condition, the data show that the maximum load which could be added was 4.75 kN and the corresponding retracted load at the same pressure was 4.69 kN. There was only 3% difference in ring transducer and pan balance reading under dynamic condition, an average of 1.02% to 6.26% difference in load during the entire length of travel w.r.t initial load was found for both bias and radial-ply tyre under different pull up to 20% slip. There was no significant difference was found between initial vertical load and average vertical load during travel as the p-value (calculated probability) was found 0.30 (> 0.05) using t-test available in SAS 9.3.

Key words: Bias-ply tyre, drawbar pull, radial-ply tyre, slips, vertical loading mechanism

The main purpose of developing a tyre testing device is to study the performance of tyres, under known normal loads, drawbar pulls and slip conditions. 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. A single tyre testing facility should have provision to measure pull, actual velocity, torque, axle rpm, tyre sinkage and dynamic normal load on the tyre. By knowing these parameters, the actual velocity, slip, tractive efficiency and coefficient of traction can be determined. Most of the soil bin devices are in indoor testing facilities, but only a few are capable of performing tyre testing under actual field condition (Yahya *et al*., 2007, Mardani *et al*., 2010). Indoor soil bin devices can provide well-controlled testing conditions. The past studies conducted on bias-ply and radial-ply tyres indicated that tractive performance of tyres is influenced by the normal load, inflation pressure, tyre deflection, tyre size, soil condition etc. Burt *et al.* (1979) investigated the role of both dynamic load and slip on tractive performance. The results of this study indicated the large changes in performance occurred at change in low values of slip. However, at higher slip changes in dynamic load had a greater effect on performance than that of changes in slip. At constant slip, tractive efficiency increased with increases in dynamic load on compacted soil. On the un-compacted soil subsurfaces, tractive efficiency decreased with the increased dynamic load. Input power increased linearly with respect to dynamic load and non-linearly with respect to slip. Output power changed in a non-linear way with respect to changes in either dynamic load or net traction.

Tiwari (2006) conducted a test and reported that the effect of the normal load is highly significant on tractive performance. The combined effect of normal load and inflation pressure is also significant on the tractive performance of tyres. Tractive efficiency of the tyres increased while the wheel slip decreased with a decrease in normal load. The increase in the slip with an increase in normal load for a constant coefficient of traction may be due to an increase in pull in proportion to the dynamic weight.

Nowadays, testing of tyres is widely carried out in Europe and America. Provisions for single wheel testing or double wheel testing exist in many countries. In the case of agricultural tyres, the testing facility may be indoor or outdoor.

Shmulevich *et al.* (1996) developed a tyre test setup driven by a low-speed hydraulic motor. The hydraulic motor and power shaft are connected to the force measuring frame via load cell assemblies. The hydraulic system is divided into two separate parts with respect to the power supply. The first part of the hydraulic system powers the test wheel. The hydraulic motor is driven by an additional engine and pump which are mounted on the rear of the tractor. The second part of the hydraulic system consists of a built-in tractor oil pump which serves as a power source for vertical loading of the test wheel. The system controls the oil pressure in the vertical cylinder and compensates for the field roughness influence on the applied load.

Wonderlich and Goodall (2007) developed a dynamic loading device for single wheel testing unit. The loading system consists of a hydraulic cylinder and an adjustable pressure relieving valve. The force developed was in the range of 23.6 kN at 20.7 N/mm^2. Dynamic wheel load is transferred from the frame to the tyre under test via hydraulic cylinder connected with a load cell and attached to the tyre test carriage and the superstructure. To manage the dynamic wheel loading successfully, 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 tractors hydraulic system. The hydraulic cylinder is connected to the tractor's hydraulic couplings through a pressure relieving valve which keeps the loading constant on the tractor tyre over varying terrain conditions.

The Agricultural and Food Engineering Department at IIT Kharagpur has an indoor soil testing facility to test the various sizes of tyres used in tractors (Tiwari *et al.,* 2009 and Kumar, 2009). This facility, though complete in many respects, still lacks accuracy and need automation in respect of vertical loading mechanism. The main purpose of the design and development of this vertical loading mechanism is to develop in automation system to quick adding or removal of normal according to the experimental plan, as well as to reduce drudgery in manual frequent loading and unloading of dead weight on the test rig during the experiments and for ease of operation.

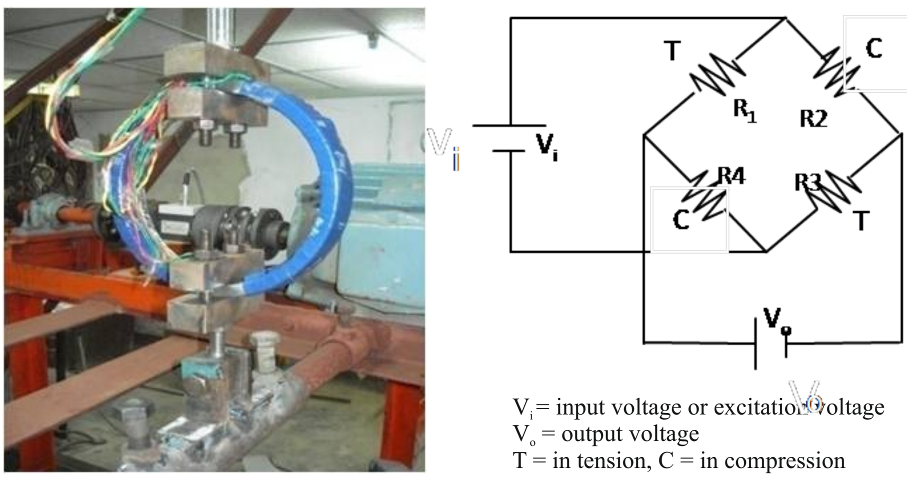
MATERIALS AND METHODS

Basic Concept of Vertical Loading Mechanism

A vertical loading mechanism based on hydraulic device reduces the labour requirement and drudgery for adjusting the vertical load on the wheel axles. In the case of manual loading and unloading, every time several weights are required to put on the crate of tyre trolley at high height. This was laborious, tiresome and time consuming operation. Vertical loading mechanism consists of an electric motor, a hydraulic pump, a reservoir, a direction control valve, a hydraulic cylinder and relief valves. In this system, a special type of directional control valve of four port three position magnetic solenoid valve is used. The corresponding pressure for a load to be applied is calculated from the mathematical calculations. The load on the wheel was known from a ring transducer mounted in between the piston rod and wheel carriage and the applied load was set by pressure relief valve with the help of a computer.

Instrumentation Used in Vertical Loading Mechanism

A proving ring of a maximum of 30 kN load bearing capacity was selected. The body of that ring was made of special steel, by forging to give maximum strength and individually tailored to give high sensitivity combined with



V_i = input voltage or excitation voltage
V_o = output voltage
T = in tension, C = in compression

Fig. 1: Instrumented ring transducer based on the principle of wheat stone bridge mounted on the wheel carriage

stability to ensure life and accuracy. Four strain gauges were oriented in the full-bridge pattern and formed a Wheatstone bridge and connected with a data acquisition system.

Before mounting the strain gauges, the surface of the ring was prepared carefully. For this, the surface was rubbed by sandpaper to remove paint and rust. Solvents were used to eliminate all traces of grease and oil. Finally, the surface was treated with a basic solution to give it the proper affinity for the adhesive. The gauge location was marked with a very light scribe line and the gauges with adhesive were positioned by using carriage transparent tape. The position and orientation of gauge were maintained. The instrumented ring transducer is shown in Fig. 1.

Calibration of the ring transducer

The ring was calibrated to develop a relationship between voltage and load. The calibration was done in both tensile modes by hanging ring transducer between fixed frame and traditional weighing balance and compression mode by keeping the ring transducer between fixed frame and hydraulic jack. In tensile (Fig. 2a) the weight is added to the balance manually and in compression (Fig. 2b) weight is given to ring transducer by means of extending the piston of hydraulic jack and amount of compressive load was noted by pan balance which is kept below the hydraulic jack. Against each load, the bridge output was recorded in Data Acquisition System (DAS) and finally a graph was prepared between applied load and output voltage.

Design of Vertical Loading Mechanism

The steps for design of hydraulic vertical loading device are as follows:

1. The tare weight of the test carriage is 7 kN. Tyres of different sizes were tested in the load range of 7 to 25 kN. Hence, the additional load required to be added on the tyre axle is upto18kN.Therefore, the design load is fixed at 18kN keeping a factor of safety of 2.
2. A maximum system pressure of 4 N/mm^2 is assumed.
3. The area of the cylinder bore is found out by using the formula.

$$F = p \times A \qquad \ldots (1)$$

Where p = Pressure, N/mm^2, A = Cylinder bore area, mm^2, and F= Thrust force, N,

4. The diameter of the cylinder bore was calculated using this formula

$$A = (\pi \times D^2 / 4) \qquad \ldots (2)$$

Where D = Cylinder bore in mm

5. The piston rod diameter is checked for buckling by using Euler's formula. The piston rod acts as a strut so Euler's strut theory is used to withstand buckling.

$$F = \frac{\pi^2 EI}{(KL)^2} \qquad \ldots (3)$$

Where, E= modulus of elasticity, I = Polar moment of inertia, K= column effective length factor, L=length of piston rod of hydraulic cylinder.

6. The piston extension velocity is assumed to be 60 mm/s to compensate for the sinkage of the tyre which hardly goes beyond 50 mm.
7. Flow rate of the pump Q is the product of cylinder area and velocity of extension.

$$Q = [A \times v] \ m^3/s \text{ where } v = \text{velocity of extension, m/s} \qquad \ldots (4)$$

8. The relief valve rating generally is 10–25% more than the operating pressure. As the operating

Fig. 2: Tensile and Compression method respectively for calibration of ring transducer

pressure is 4 N/mm^2, a relief valve of 5N/mm^2 is chosen which is well within the range recommended.

9. The hydraulic power developed by the pump is given by

N = P x Q Where, P= maximum system pressure … (5)

10. The size of the reservoir was kept 3 times the pump flow rate. The required capacity of reservoir may be obtained by multiplying the time required to complete the extend stroke i.e. 5 s,

Then reservoir capacity = $\frac{Q x 5}{60}$

Development of Vertical Loading Mechanism

An appropriate hydraulic loading mechanism was designed and developed (Fig. 3a) to manage the vertical loading on the wheel axle. It replaced the manual method of loading and unloading the dead weight on the tyre carriage which is shown in Fig. 3b. The circuit diagram is shown in Fig. 4. The system was capable of both adding and withdrawing load from the wheel axle. Table 1 represents the hydraulic circuit flow path and activity table for extraction and retraction of the hydraulic cylinder piston for load adjustment.

Mounting of the Hydraulic system on Tyre Test Carriage

The double acting hydraulic cylinder is mounted in such a position that the piston rod would position vertical to the plane of carriage and just above the axle of the tyre.

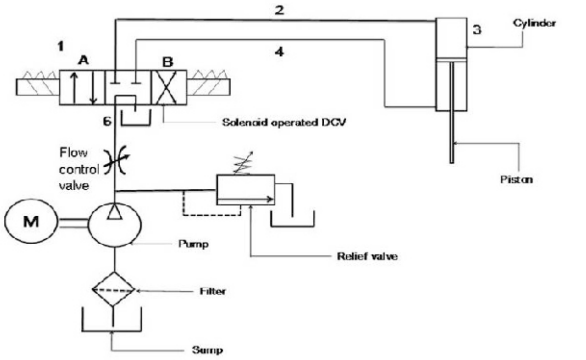


Fig. 4: Hydraulic circuit diagram for the normal loading system

Preferably it is fixed to the frame which is supported from the trolley behind the main carriage. The arrangement of installation of hydraulic cylinder is shown in Fig. 5.

A 4-ports, 3-positions double direction control solenoid valve was used to extend or retract and thereby increase or decrease the load on the tyre from a remote distance. The selection of the 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. Hydraulic oil of ISO 68 grade was chosen to ensure the proper functioning of the system. The size of the hose selected for this circuit is of 6.35 mm inner diameter with maximum pressure bearing capacity of 22.5 N/mm^2, which is more than 5 times the maximum

1. Hydraulic cylinder, 2. Solenoid operated Directional Control Valve (DCV), 3. Relief valve, 4.Reservoir, 5. Electric motor, and 6. Pump

Fig. 3: (a) Vertical load applying on wheel axle by hydraulic device and (b) Manual method of putting dead weight

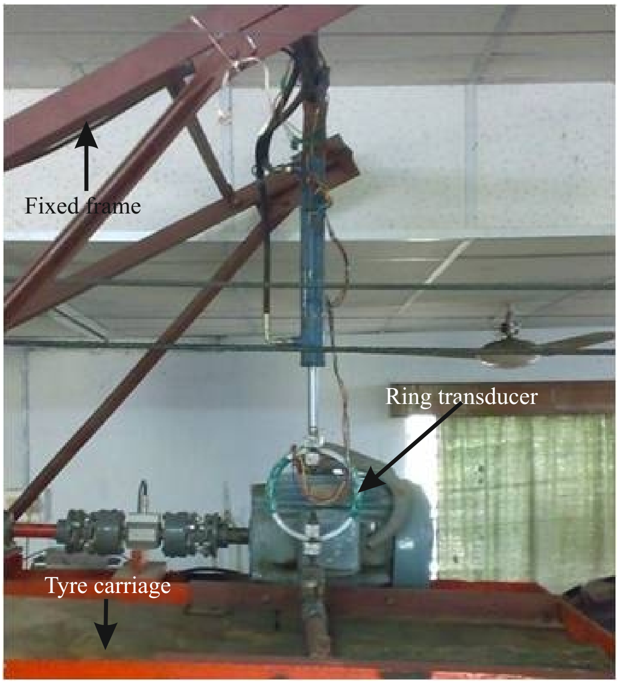


Fig. 5: Hydraulic cylinder mounted over the tyre test carriage

operating pressure. The detail of designed and the selection of hydraulic components have shown in Table 2.

Statistical Analysis

An experiment for the validation of hydraulic vertical loading mechanism was carried out to collect data based on initial static vertical load (L1) and average vertical load during travel (L2). The difference between L1and L2 was tested using t-test procedure available in SAS 9.3. The significance of equality of variances of L1 and L2 were tested using Folded F method before making inferences about the significant difference between L1 and L2 in case of equal/unequal variances. The interpretations of the results of statistical analysis have been carried out at 5% level of significance.

RESULTS AND DISCUSSION

Calibration of Ring Transducer

The ring transducer was calibrated as per the standard procedure. The results are shown in the Fig. 6. A linear relationship was found between average load and voltage

Table 1: Hydraulic circuit flow path and activity table

Position of piston rod	Directional Control Valve position, solenoid A	Directional Control Valve position, solenoid B	Fluid flow path	Result
Extended	On	Off	Advance :1-2-3 Return: 4-5	Load addition
Retracted	Off	On	Advance: 6-4 Return: 3-2-1-5	Load reduction
Extended at desired pressure	On	Off	Advance: 1-2-3 Return: 4-5	Load is maintained

Table 2: 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: 60mm/s Return stroke speed: 82.4 mm /s Pressure range: 0–4N/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: 0–5N/mm^2	Type: direct operated variable Pressure rating: 0–5N/mm^2
6.	Reservoir capacity	0.015 m^3	0.015 m^3

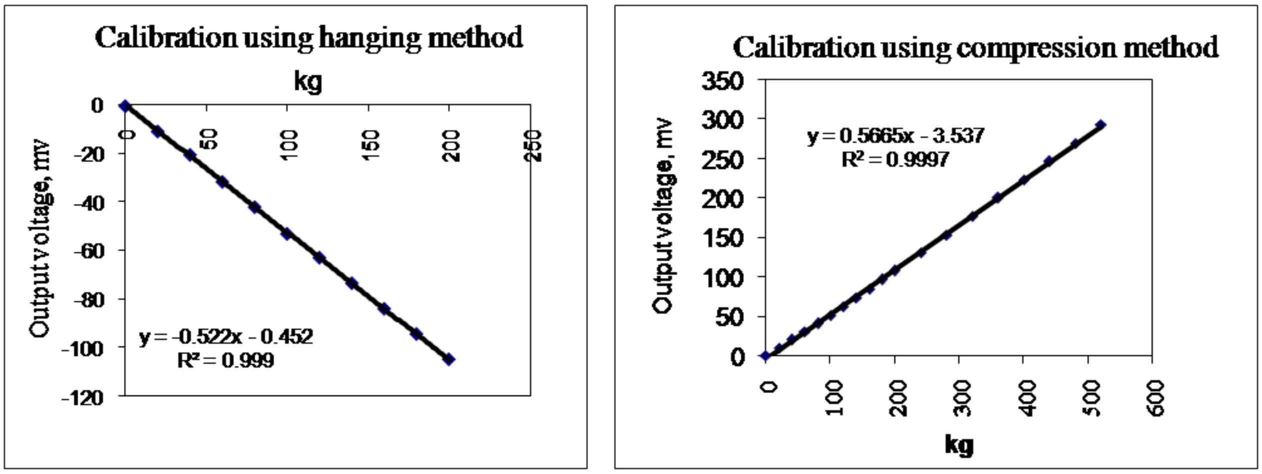


Fig. 6: Calibration curve of ring transducer

output for both tensile and compression loading of ring transducer.

Evaluation of vertical loading mechanism

Vertical loading mechanism was validated by hydraulic loading of test tyres under both static and dynamic conditions. Validation of hydraulic normal loading was done with test tyres under static and dynamic Condition. The wheel carriage was given an additional static load of 0–4.9 kN by a hydraulic device during extending and retract strokes and the value indicated by the pan balance and those sensed by the ring transducer were recorded. The percentage difference in both readings was calculated. The load recorded in pan balance and load sensed by ring transducer were compared. The percentage difference between initial vertical loads (7.85 N, 8.83 N and 10.30 N) and the average of vertical load during travel of test tyre carriage was calculated under the dynamic condition for both bias and radial ply tyres in soft soil condition. The pull was given to test tyre carriage till 20% of slip achieved. A bias-ply tyre and a radial-ply tyre, each of 13.6x28 size, were tested under this study in soft soil conditions. The load was varied from 7.85 kN to 10.30 kN using the hydraulic vertical loading mechanism under both static and dynamic conditions. The soil cone index was maintained at 0.60 N/mm^2 to 0.800 N/mm^2. The inflation pressure maintained in the bias-ply tyre was kept 0.60 N/mm^2 at 7.85 kN load, 0.10 N/mm^2 at 8.83 kN load and 1.0 N/mm^2 at 10.3 kN load. The inflation pressure maintained in the radial tyre was 0.20 N/mm^2 less than the pressure in bias-ply tyre at different loads to keep the same deflection of both tyres.

Evaluation of vertical loading mechanism in static condition

Under the static condition, the wheel carriage was given an additional static load up to 4 N/mm^2 pressure of relieve value by the hydraulic device during extend and retract strokes and the value indicated by the pan balance and those sensed by the ring transducer were recorded which and given in Table 3.

The data show that the maximum load which could be added was 4.75 kN and the corresponding retracted load at

Table 3: Evaluation of vertical loading mechanism under static condition

Pressure, N/mm^2	Extend stroke			Retract stroke		
	Load sensed by ring transducer, kN	load recorded in pan balance, kN	% difference	load sensed by ring transducerkN	load recorded in pan balance,kN	% difference
0	0.00	0.00	0.00	0.00	0.00	0.00
0.5	0.50	0.49	2.48	0.44	0.42	3.19
0.1	0.95	0.93	2.37	0.88	0.85	2.70
1.5	1.63	1.60	1.75	1.31	1.29	1.54
2.0	2.09	2.05	1.94	1.75	1.72	2.12
2.5	2.72	2.70	0.80	2.19	2.15	2.00
3.0	3.67	3.65	0.62	2.63	2.59	1.54
3.5	4.18	4.12	1.35	3.07	3.03	1.21
4.0	4.75	4.69	1.39	3.51	3.45	1.54

Table 4: Percentage average difference in vertical load w.r.t. initial load during dynamic condition for bias ply tyre and radial ply tyre

Pull (kN)	Slip (%)	Avg. vertical load during travel (kN)	% avg. diff. in load w.r.t. initial load
		For bias ply tyre	
		At 7.85 kN initial vertical load	
0.00	0.95	7.95	1.28
0.94	3.19	8.01	2.05
2.05	8.75	8.15	3.80
2.87	19.11	8.23	4.85
3.03	20.22	8.24	5.06
		At 8.83 kN initial vertical load	
0	1.52	8.97	1.59
0.88	3.65	8.94	1.31
1.99	8.16	9.14	3.58
2.77	15.91	9.35	5.95
3.21	19.35	9.38	6.26
		At 10.30 kN initial vertical load	
0	1.46	10.51	2.06
0.93	2.69	10.50	1.96
1.99	8.26	10.58	2.76
2.92	15.02	10.84	5.20
3.52	19.85	10.89	5.76
		For radial ply tyre	
		At 7.85 kN initial vertical load	
0.00	0.98	7.93	1.02
0.90	1.14	7.98	1.68
2.03	3.21	8.11	3.31
3.46	14.23	8.19	4.4
3.81	21.32	8.25	5.17
		At 8.83 kN initial vertical load	
0	1.12	9.06	2.62
0.94	1.9	9.05	2.51
2.00	2.39	9.11	3.16
2.86	9.12	9.17	3.86
3.97	19.55	9.22	4.44
		At 10.30 kN initial vertical load	
0	1.25	10.59	2.8
1.20	1.95	10.60	2.9
2.10	5.59	10.63	3.22
3.33	13.43	10.70	3.84
4.14	20.12	10.77	4.57

Table 5: Equality of variances

Test for Equality of variances of input and output

Tire	p value
Bias ply	0.78
Radial ply	0.81

Table 6: Difference between input and output

Test for difference between input and output

Tire	Pr>|t|	95 % confidence interval of mean
Bias ply	0.3024	Initial: 875.5-970; Final: 907.2-1007.5
Radial ply	0.3023	Initial: 868.5-955.5; Final: 898.2-989.5

the same pressure was 4.69kN. Maximum 3% difference was found between the load reading taken by ring transducer and pan balance in static condition.

Evaluation of vertical loading mechanism in static condition

The percentage difference between initial vertical static loads and average vertical load in dynamic condition was calculated which is shown in Table 4. For bias-ply tyre at initial vertical load at 7.85, 8.83 and 10.30 kN, the percentage average difference in load in dynamic condition w.r.t initial static load condition was found to be in the range of 1.28 to 5.06%, 1.59 to 6.26% and 2.06 to 5.76%, respectively. For radial-ply tyre, the same was found to be in the rage of 1.02 to 5.17%, 2.62 to 4.44% and 2.8 to 4.57%, respectively. Overall, the average difference in their loads w.r.t initial load was found for both bias and radial-ply tyre under different pull up to 20% slip to be in the range of 1.02% to 6.26%

Statistical Analysis

The equality of variances of L1 and L2 were tested and the null hypothesis that variances were equal, could not be rejected because p-value was found to be 0.78 (> 0.05). As variances of L1 and L2 were equal, the t-test in case of equal variances was judged. It was concluded that there was no significant difference between L1 and L2 as p-value found to be 0.30 (> 0.05). Also, in case of unequal variances, there was no significant difference between L1 and L2. The same experiment and statistical analysis were performed for second tire also. The result of the analysis for both the tires bias and radial ply along with mean and 95 % confidence interval have been given in Table 5 and 6.

CONCLUSION

A vertical loading mechanism based on a hydraulic device would be able to reduce the labour requirement and this mechanism eliminates drudgery to the operator during adding weight to the tyre test carriage. A vertical loading mechanism which was made by means of hydraulic system was design and developed to provide a vertical load up to 25 kN on wheel axle and the same device can be used to remove 13 kN load. In a dynamic mode of operation, minimum and maximum average percentage difference in load during the entire length of travel was found to be 1.02% and 6.26% as compared to initial load under different pull within 20% slip. There was no significant difference between the initial vertical load and average vertical load during travel as p-value found to be 0.30 (> 0.05). The performance of the radial-ply tyre was found better than that of the bias-ply tyre, which developed 15 to 20 % more drawbar pull at same slip as compared to bias-ply tyre.

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